

| | |
|---------------|---|
| Title | ON THE FLAT GEOMETRY OF THE CUSPIDAL EDGE |
| Author(s) | Oset Sinha, Raúl; Tari, Farid |
| Citation | Osaka Journal of Mathematics. 55(3) p.393-p.421 |
| Issue Date | 2018-07 |
| oaire:version | VoR |
| URL | https://doi.org/10.18910/70079 |
| rights | |
| Note | |

Osaka University Knowledge Archive : OUKA

<https://ir.library.osaka-u.ac.jp/>

Osaka University

ON THE FLAT GEOMETRY OF THE CUSPIDAL EDGE

RAÚL OSET SINHA* and FARID TARI**

(Received March 9, 2016, revised December 21, 2016)

Abstract

We study the geometry of the cuspidal edge M in \mathbb{R}^3 derived from its contact with planes and lines (referred to as flat geometry). The contact of M with planes is measured by the singularities of the height functions on M . We classify submersions on a model of M by diffeomorphisms and recover the contact of M with planes from that classification. The contact of M with lines is measured by the singularities of orthogonal projections of M . We list the generic singularities of the projections and obtain the generic deformations of the apparent contour (profile) when the direction of projection varies locally in S^2 . We also relate the singularities of the height functions and of the projections to some geometric invariants of the cuspidal edge.

1. Introduction

Let $\phi: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be a parametrisation of a surface M , where U is an open set and ϕ is an infinitely differentiable map. The surface M is called a *cuspidal edge* if it admits a parametrisation ϕ which is \mathcal{A} -equivalent to $f(x, y) = (x, y^2, y^3)$, that is, there exist diffeomorphisms h and k such that $\phi = k \circ f \circ h^{-1}$. Our study is local in nature so we consider germs of parametrisations of a cuspidal edge. Observe that the cuspidal edge is singular along a curve and its trace on a plane transverse to this curve is a curve with a cusp singularity, see Figure 1 (middle figure).

Cuspidal edges occur naturally in differential geometry. For instance, given a regular surface M in \mathbb{R}^3 , one can consider its parallel M_d , which is the surface obtained by moving the points on M along a chosen unit normal vector to M by a fixed distance d . The parallel M_d can become singular and is, in general, a cuspidal edge with its singularities corresponding to points on the surface where $d = 1/\kappa_i$, $i = 1, 2$, κ_i 's being the principal curvatures. (The singularities of M_d can become more degenerate than a cuspidal edge on some special curves on the surface M .) Another example is the focal set (caustic) of a surface in \mathbb{R}^3 . If we take a parametrisation where the lines of curvature are the coordinate curves $x_i = \text{constant}$, $i = 1, 2$, then the focal set is a cuspidal edge at generic points on the curves $\partial\kappa_i/\partial x_i = 0$, $i = 1, 2$.

Because cuspidal edges occur naturally and in a stable way in some cases, it is of interest to study their differential geometry. There is already work in this direction, see for example [9, 17, 18, 19, 22, 24, 27].

In this paper, we study the geometry of the cuspidal edge M derived from its contact with planes and lines (which is referred to as the flat geometry of M as planes and lines are flat

2010 Mathematics Subject Classification. 57R45, 53A05.

*Supported by DGCYT and FEDER grant no. MTM2012-33073.

**Partially supported by the grants FAPESP 2014/00304-2, CNPq 301589/2012-7, 472796/2013-5.

objects, i.e., have zero curvature). Consider parallel planes orthogonal to $\mathbf{v} \in S^2$, where S^2 denotes the unit sphere in \mathbb{R}^3 . These planes are the fibres of the function $h_{\mathbf{v}}(p) = p \cdot \mathbf{v}$, where “ \cdot ” is the scalar product in \mathbb{R}^3 . The contact of M with the above planes at $p_0 = \phi(0, 0)$ is measured by the singularities of $h_{\mathbf{v}} \circ \phi$ at the origin. By varying \mathbf{v} , we get the family of height functions $H : U \times S^2 \rightarrow \mathbb{R}$ on M given by

$$H((x, y), \mathbf{v}) = \phi(x, y) \cdot \mathbf{v}.$$

In the above setting the model (flat) surfaces in \mathbb{R}^3 are planes and the parametrisation ϕ is taken in general form. In this paper, we follow the approach in [8] and invert the situation: we fix the \mathcal{A} -model X of the cuspidal edge as the image of the map-germ $f(x, y) = (x, y^2, y^3)$ and consider its contact with fibres of submersions.

We classify in §3 submersion $\mathbb{R}^3, 0 \rightarrow \mathbb{R}$ up to changes of coordinates in the source that preserve the model cuspidal edge X . Such changes of coordinates form a geometric subgroup $\mathcal{R}(X)$ of the Mather group \mathcal{R} (see [11]). In §3.1, we deduce from that classification the generic geometry of a cuspidal edge M derived from its contact with planes. We study the duals of these generic cases. Other results on duals of cuspidal edges can be found in [24].

The contact of M with lines is measured by the \mathcal{A} -singularities of orthogonal projections of M to planes. Here too we fix the model cuspidal edge X and classify in §4 the singularities of germs of submersions $\mathbb{R}^3, 0 \rightarrow \mathbb{R}^2, 0$ under the action of the subgroup ${}_X\mathcal{A} = \mathcal{R}(X) \times \mathcal{L}$ of the Mather group \mathcal{A} . This approach has an important advantage to considering the \mathcal{A} -singularities of the orthogonal projections on M (or the \mathcal{R} -singularities of the height functions on M). Using a transversality result from [8] adapted to our situation, we can state that only the singularities of ${}_X\mathcal{A}_e$ -codimension ≤ 2 can occur for a generic cuspidal edge M . Furthermore, we associate a natural 2-parameter family of submersions $\mathbb{R}^3, 0 \rightarrow \mathbb{R}^2, 0$ on the model X obtained from the family of orthogonal projections of M to planes. This family is an ${}_X\mathcal{A}_e$ -versal unfolding of the generic singularities of the submersions on X . This allows us to obtain in §4.1 the generic deformations of the apparent contour (profile) of M when the direction of projection varies locally in S^2 .

2. Preliminaries

We review in this section some aspects of the geometry of the cuspidal edge (§2.1) and establish some notation (§2.2) for the classification of germs of functions and mappings on the cuspidal edge.

2.1. Geometric cuspidal edge. Let M be a general cuspidal edge in \mathbb{R}^3 which we shall refer to (following the notation in [8]) as a geometric cuspidal edge. In [18] a local parametrisation (at the origin) of the cuspidal edge is given by allowing any changes of coordinates in the source and changes of coordinates in the target given by isometries. That parametrisation, which we shall adopt in the rest of the paper, is the following

$$(1) \quad \phi(x, y) = (x, a(x) + \frac{1}{2}y^2, b_1(x) + y^2b_2(x) + y^3b_3(x, y)),$$

with (x, y) in a neighbourhood of the origin and $a(0) = a'(0) = 0$, $b_1(0) = b'_1(0) = 0$, $b_2(0) = 0$, $b_3(0) \neq 0$. Following the notation in [18], we write

$$\begin{aligned} a(x) &= \frac{1}{2}a_{20}x^2 + \frac{1}{6}a_{30}x^3 + \frac{1}{24}a_{40}x^4 + O(5), \\ b_1(x) &= \frac{1}{2}b_{20}x^2 + \frac{1}{6}b_{30}x^3 + \frac{1}{24}b_{40}x^4 + O(5), \\ b_2(x) &= \frac{1}{2}b_{12}x + \frac{1}{6}b_{22}x^2 + O(3), \\ b_3(x, y) &= \frac{1}{6}b_{03} + \frac{1}{6}b_{13}x + O(2). \end{aligned}$$

The tangential direction of M at the origin is along $(1, 0, 0)$ and its tangent cone is the plane $w = 0$, where (u, v, w) are the coordinates of \mathbb{R}^3 . The singular set Σ of M is the image of the line $y = 0$ and is parametrised by $\alpha(x) = \phi(x, 0) = (x, a(x), b_1(x))$.

If we denote by κ_Σ and τ_Σ the curvature and the torsion of Σ as a space curve, then

$$\begin{aligned} \kappa_\Sigma(0) &= \sqrt{a_{20}^2 + b_{20}^2}, \\ \tau_\Sigma(0) &= \frac{a_{20}b_{30} - b_{20}a_{30}}{a_{20}^2 + b_{20}^2}, \\ \tau'_\Sigma(0) &= \frac{1}{a_{20}^2 + b_{20}^2} \left(a_{20}b_{40} - b_{20}a_{40} - \frac{2}{a_{20}^2 + b_{20}^2} (a_{20}b_{30} - b_{20}a_{30})(a_{20}a_{30} + b_{20}b_{30}) \right). \end{aligned}$$

The osculating plane of Σ at the origin is orthogonal to the vector $(0, -b_{20}, a_{20})$. It coincides with the tangent cone to M at the origin if and only if $b_{20} = 0$. It is worth observing that this happens if and only if the closure of the parabolic curve of the regular part of M intersects the singular set Σ .

Recall that a smooth curve has contact of type $A_{\geq 1}$ at a point p with any of its tangent planes at p , of type $A_{\geq 2}$ if the plane is the osculating plane at p and of type A_3 if furthermore the torsion of the curve vanishes at p but the derivative of the torsion is not zero at that point (see for example [2]). In [22] other invariants of the cuspidal edge are defined. These are:

- The singular curvature κ_s ($\kappa_s(0) = a_{20}$);
- The limiting normal curvature κ_n ($\kappa_n(0) = b_{20}$);
- The cuspidal curvature κ_c ($\kappa_c(0) = b_{03}$);
- The cusp-directional torsion κ_t ($\kappa_t(0) = b_{12}$);
- The edge inflectional curvature κ_i ($\kappa_i(0) = b_{30}$).

The contact of M with lines and planes is affine invariant ([4]), so we can allow affine changes of coordinates in the target without changing the type of contact. Given a parametrisation $\phi : \mathbb{R}^2, 0 \rightarrow \mathbb{R}^3, 0$ of a cuspidal edge, we can make a rotation in the target and changes of coordinates in the source and write $j^2\phi(x, y) = (x, Q_1(x, y), Q_2(x, y))$, with Q_1, Q_2 homogeneous polynomials of degree 2. We can consider the $\mathcal{G} = GL(2, \mathbb{R}) \times GL(2, \mathbb{R})$ -action on the set of pairs of quadratic forms (Q_1, Q_2) . Following [18], we can set $(Q_1, Q_2) = (\frac{a_{20}}{2}x^2 + \frac{1}{2}y^2, \frac{b_{20}}{2}x^2)$ by isometric changes of coordinates in the target and any smooth changes of coordinates in the source, and this is \mathcal{G} -equivalent to

$$\begin{aligned} (y^2, x^2) & \quad \text{if and only if } b_{20} \neq 0 \text{ (hyperbolic)} \\ (\pm x^2 + y^2, 0) & \quad \text{if and only if } b_{20} = 0, a_{20} \neq 0 \text{ (inflection)} \\ (y^2, 0) & \quad \text{if and only if } b_{20} = a_{20} = 0 \text{ (degenerate inflection)} \end{aligned}$$

The above \mathcal{G} -classes are the only ones that can occur for the pair (Q_1, Q_2) associated to a parametrisation of a cuspidal edge. In particular, most points on Σ are hyperbolic points for the pair (Q_1, Q_2) , and we have an inflection point if and only if the osculating plane of Σ coincides with the tangent cone to M .

Following the above discussion, we can take (Q_1, Q_2) associated to ϕ in (1) in one of

the \mathcal{G} normal forms above. However, we shall work with the parametrisation (1) so that the interpretation of the conditions we get here match some of the invariants in [18].

2.2. Classification tools. Let \mathcal{E}_n be the local ring of germs of functions $\mathbb{R}^n, 0 \rightarrow \mathbb{R}$ and \mathcal{M}_n its maximal ideal. Denote by $\mathcal{E}(n, p)$ the p -tuples of elements in \mathcal{E}_n . Let $\mathcal{A} = \mathcal{R} \times \mathcal{L}$ denote the group of pairs of germs of diffeomorphisms of the source and target, which acts smoothly on $\mathcal{M}_n \cdot \mathcal{E}(n, p)$ by $(k_1, k_2) \cdot G = k_2 \circ G \circ k_1^{-1}$. The tangent space to the \mathcal{A} -orbit of F at the germ F is given by

$$L\mathcal{A} \cdot F = \mathcal{M}_n \cdot \{F_{x_1}, \dots, F_{x_n}\} + F^*(\mathcal{M}_p) \cdot \{e_1, \dots, e_p\},$$

where F_{x_i} are the partial derivatives of F with respect to x_i ($i = 1, \dots, n$), e_1, \dots, e_p denote the standard basis vectors of \mathbb{R}^p considered as elements of $\mathcal{E}(n, p)$, and $F^*(\mathcal{M}_p)$ is the pull-back of the maximal ideal in \mathcal{E}_p . The extended tangent space to the \mathcal{A} -orbit of F at the germ F is given by

$$L_e \mathcal{A} \cdot F = \mathcal{E}_n \cdot \{F_{x_1}, \dots, F_{x_n}\} + F^*(\mathcal{E}_p) \cdot \{e_1, \dots, e_p\},$$

and the codimension of the extended orbit is $d_e(F, \mathcal{A}) = \dim_{\mathbb{R}}(\mathcal{E}(n, p)/L_e \mathcal{A}(F))$.

Let $k \geq 1$ be an integer. We denote by $J^k(n, p)$ the space of k th order Taylor expansions without constant terms of elements of $\mathcal{E}(n, p)$ and write $j^k F$ for the k -jet of F . A germ F is said to be k - \mathcal{A} -determined if any G with $j^k G = j^k F$ is \mathcal{A} -equivalent to F (notation: $G \sim_{\mathcal{A}} F$). The k -jet of F is then called a sufficient jet.

Let \mathcal{G} be one of the groups $\mathcal{R}, \mathcal{L}, \mathcal{A}$. Let \mathcal{G}_k be the subgroup of \mathcal{G} with elements with k -jet the identity. The group \mathcal{G}_k is a normal subgroup of \mathcal{G} . Define $\mathcal{G}^{(k)} = \mathcal{G}/\mathcal{G}_k$, which is a Lie group. The elements of $\mathcal{G}^{(k)}$ are the k -jets of the elements of \mathcal{G} . The action of \mathcal{G} on $\mathcal{M}_n \cdot \mathcal{E}(n, p)$ induces an action of $\mathcal{G}^{(k)}$ on $J^k(n, p)$ as follows. For $j^k f \in J^k(n, p)$ and $j^k h \in \mathcal{G}^{(k)}$, $j^k h \cdot j^k f = j^k(h \cdot f)$.

Our goal in §3 and §4 is to classify germs of functions and mappings on $X \subset \mathbb{R}$, where X is the germ of the smooth model of a cuspidal edge. This means that we require that the diffeomorphisms in \mathbb{R}^3 preserve X . Such diffeomorphisms are obtained by integrating vector fields tangent to X and form a subgroup $\mathcal{R}(X)$ (${}_X \mathcal{R}$ in some texts) of the group \mathcal{R} . We denote by ${}_X \mathcal{A} = \mathcal{R}(X) \times \mathcal{L}$ the subgroup \mathcal{A} where the diffeomorphisms in the source preserve X .

3. Functions on a cuspidal edge

Given the \mathcal{A} -normal form $f(x, y) = (x, y^2, y^3)$ of a cuspidal edge, we classify germs of submersions $g : \mathbb{R}^3, 0 \rightarrow \mathbb{R}, 0$ up to $\mathcal{R}(X)$ -equivalence, with $X = f(\mathbb{R}^2, 0)$. The defining equation of X is given by $h(u, v, w) = v^3 - w^2$.

Let $\Theta(X)$ be the \mathcal{E}_3 -module of vector fields in \mathbb{R}^3 tangent to X . We have $\xi \in \Theta(X)$ if and only if $\xi h = \lambda h$ for some function λ ([8, page 21]).

Proposition 3.1. *The \mathcal{E}_3 -module $\Theta(X)$ of vector fields in \mathbb{R}^3 tangent to X is generated by the vector fields*

$$\begin{aligned}\xi_1 &= \frac{\partial}{\partial u}, \\ \xi_2 &= 2v \frac{\partial}{\partial v} + 3w \frac{\partial}{\partial w},\end{aligned}$$

$$\xi_3 = 2w \frac{\partial}{\partial v} + 3v^2 \frac{\partial}{\partial w}.$$

Proof. The defining equation $h(u, v, w) = v^3 - w^2$ of X is weighted homogenous in v and w with weights 2 and 3 respectively. The result follows by applying Proposition 7.2 in [7] for isolated singularities to the cusp $v^3 - w^2 = 0$ in the (v, w) -plane and adding the trivial vector field ξ_1 in \mathbb{R}^3 . \square

Let $\Theta_1(X) = \{\delta \in \Theta(X) : j^1 \delta = 0\}$. It follows from Proposition 3.1 that

$$\Theta_1(X) = \mathcal{M}_3^2 \cdot \{\xi_1\} + \mathcal{M}_3 \cdot \{\xi_2, \xi_3\}.$$

For $f \in \mathcal{E}_3$, we define

$$\Theta(X) \cdot f = \mathcal{M}_3 \cdot \{\xi_1(f)\} + \mathcal{E}_3 \cdot \{\xi_2(f), \xi_3(f)\}.$$

We define similarly $\Theta_1(X) \cdot f$ and the following tangent spaces to the $\mathcal{R}(X)$ -orbit of f at the germ f :

$$\begin{aligned} L\mathcal{R}(X) \cdot f &= \Theta(X) \cdot f \\ L\mathcal{R}_1(X) \cdot f &= \Theta_1(X) \cdot f \\ L\mathcal{R}_e(X) \cdot f &= \mathcal{E}_3 \cdot \{\xi_1(f), \xi_2(f), \xi_3(f)\}. \end{aligned}$$

The classification (i.e., the listing of representatives of the orbits) of $\mathcal{R}(X)$ -finitely determined germs is carried out inductively on the jet level. The method used here is that of the complete transversal [5] adapted for the $\mathcal{R}(X)$ -action. We have the following result which is a version of Theorem 3.11 in [8] for the group $\mathcal{R}(X)$.

Proposition 3.2. *Let $f : \mathbb{R}^3, 0 \rightarrow \mathbb{R}, 0$ be a smooth germ and h_1, \dots, h_r be homogeneous polynomials of degree $k + 1$ with the property that*

$$\mathcal{M}_3^{k+1} \subset L\mathcal{R}_1(X) \cdot f + \mathbb{R} \cdot \{h_1, \dots, h_r\} + \mathcal{M}_3^{k+2}.$$

Then any germ g with $j^k g(0) = j^k f(0)$ is $\mathcal{R}_1(X)$ -equivalent to a germ of the form $f(x) + \sum_{i=1}^r u_i h_i(x) + \phi(x)$, where $\phi(x) \in \mathcal{M}_n^{k+2}$. The vector subspace $\mathbb{R} \cdot \{h_1, \dots, h_r\}$ is called a complete $(k + 1)$ - $\mathcal{R}(X)$ -transversal of f .

Theorem 3.3. *A germ $f \in \mathcal{M}_3$ is k - $\mathcal{R}_1(X)$ -determined if and only if*

$$\mathcal{M}_3^{k+1} \subset L\mathcal{R}_1(X) \cdot f + \mathcal{M}_3^{k+2}.$$

Proof. This is Theorem 2.5 in [6] applied to our setting. \square

We have the following concepts, similar to those in Definition 3.8 in [8]. A germ of a smooth 1-parameter family of functions $F : \mathbb{R}^3 \times \mathbb{R}, (0, 0) \rightarrow \mathbb{R}, 0$ with $F(0, t) = 0$ for t small is said to be k - $\mathcal{R}(X)$ -trivial if there exists a germ of a 1-parameter family of diffeomorphisms $H : \mathbb{R}^3 \times \mathbb{R}, (0, 0) \rightarrow \mathbb{R}^3, 0$, with H_t preserving X , such that $H(x, 0) = 0$, $H(0, t) = 0$ (for small t) and $F(H(x, t), t) = F(x, 0) + \psi(x, t)$ for some $\psi \in \mathcal{M}_3^{k+1} \subset \mathcal{E}_4$. If $\psi \equiv 0$, then F is said to be $\mathcal{R}(X)$ -trivial.

We need the following result about trivial families.

Proposition 3.4 ([8, Proposition 3.9]). *Let $F : \mathbb{R}^3 \times \mathbb{R}, (0, 0) \rightarrow \mathbb{R}, 0$ be a smooth family of functions with $F(0, t) = 0$ for t small. Let ξ_1, \dots, ξ_p be vector fields in $\Theta(X)$ vanishing at $0 \in \mathbb{R}^n$. Then the family F is $k\text{-}\mathcal{R}(X)$ -trivial if*

$$\frac{\partial F}{\partial t} \in \mathcal{E}_4 \cdot \{\xi_1(F), \dots, \xi_p(F)\} + \mathcal{M}_3^{k+1} \subset \mathcal{E}_4.$$

Here, when deforming germs of functions we are interested in locating the singularities of the deformed germs but not their levels. For this reason, we use the following definition (see for example [2] for the notion (p)-unfoldings).

Two families of germs of functions F and $G : \mathbb{R}^3 \times \mathbb{R}^l, (0, 0) \rightarrow \mathbb{R}, 0$ are $P\text{-}\mathcal{R}^+(X)$ -equivalent if there exist a germ of a diffeomorphism $\Phi : \mathbb{R}^3 \times \mathbb{R}^l, (0, 0) \rightarrow \mathbb{R}^3 \times \mathbb{R}^l, (0, 0)$ preserving $X \times \mathbb{R}^l, (0, 0)$ and of the form $\Phi(x, u) = (\alpha(x, u), \psi(u))$ and a germ of a function $c : (\mathbb{R}^l, 0) \rightarrow \mathbb{R}$ such that $G(x, u) = F(\Phi(x, u)) + c(u)$.

A family F is said to be an $\mathcal{R}^+(X)$ -versal deformation of $F_0(x) = F(x, 0)$ if any other deformation G of F_0 can be written in the form $G(x, u) = F(\Phi(x, u)) + c(u)$ for some germs of smooth mappings Φ and c as above with Φ not necessarily a germ of diffeomorphism.

Given a family of germs of functions F , we write $\dot{F}_i(x) = \frac{\partial F}{\partial u_i}(x, 0)$. The following result is a version of Theorem 3.6 in [8].

Proposition 3.5. *A deformation $F : \mathbb{R}^3 \times \mathbb{R}^l, (0, 0) \rightarrow \mathbb{R}, 0$ of a germ of a function f on X is $\mathcal{R}^+(X)$ -versal if and only if*

$$L\mathcal{R}_e(X) \cdot f + \mathbb{R} \cdot \{1, \dot{F}_1, \dots, \dot{F}_l\} = \mathcal{E}_3.$$

Following Proposition 3.5 and the discussion preceeding it, we define the $\mathcal{R}_e^+(X)$ -codimension of f as $d(f, \mathcal{R}_e^+(X)) = \dim_{\mathbb{R}}(\mathcal{M}_3/L\mathcal{R}_e(X)(f))$. It is the least number of parameters needed to have an $\mathcal{R}^+(X)$ -versal family.

We also use the following lemma.

Lemma 3.6 (Mather's Lemma). *Let $\alpha : G \times M \rightarrow M$ be a smooth action of a Lie group G on a manifold M , and let V be a connected submanifold of M . Then V is contained in a single orbit if and only if the following hold:*

- (a) $T_v V \subseteq T_v(G.v), \forall v \in V$,
- (b) $\dim T_v(G.v)$ is independent of $v \in V$.

We can now state the result about the $\mathcal{R}(X)$ -classification of germs of submersions.

Theorem 3.7. *Let X be the germ of the \mathcal{A} -model of the cuspidal edge parametrised by $f(x, y, z) = (x, y^2, y^3)$. Denote by (u, v, w) the coordinates in the target. Then any $\mathcal{R}(X)$ -finitely determined germ of a submersion in \mathcal{M}_3 with $\mathcal{R}_e^+(X)$ -codimension ≤ 2 (of the stratum in the presence of moduli) is $\mathcal{R}(X)$ -equivalent to one of the germs in Table 1.*

Proof. To simplify notation, we write complete k -transversal for complete $k\text{-}\mathcal{R}(X)$ -transversal, equivalence for $\mathcal{R}(X)$ -equivalence and codimension for $\mathcal{R}_e^+(X)$ -codimension. In all the proof, ξ_1, ξ_2, ξ_3 are as in Proposition 3.1.

The linear changes of coordinates in $\mathcal{R}(X)$ obtained by integrating the 1-jets of vector fields in $\Theta(X)$ are

Table 1. Germs of submersions in \mathcal{M}_3 of $\mathcal{R}_e^+(X)$ -codimension ≤ 2 .

| Normal form | $d(f, \mathcal{R}_e^+(X))$ | $\mathcal{R}^+(X)$ -versal deformation |
|--|----------------------------|--|
| u | 0 | u |
| $\pm v \pm u^2$ | 0 | $\pm v \pm u^2$ |
| $\pm v + u^3$ | 1 | $\pm v + u^3 + a_1 u$ |
| $\pm v \pm u^4$ | 2 | $\pm v \pm u^4 + a_2 u^2 + a_1 u$ |
| $w + u^2$ | 1 | $w + u^2 + a_1 v$ |
| $w + uv + au^3, a \neq 0, -\frac{4}{27}$ | $2^{(*)}$ | $w + uv + au^3 + a_2 u^2 + a_1 u$ |

(*) : a is a modulus and the codimension is that of the stratum.

$$\eta_1(u, v, w) = (\alpha u + \beta v + \gamma w, v, w), \alpha \neq 0$$

$$\eta_2(u, v, w) = (u, e^{2\alpha} v, e^{3\alpha} w), \alpha \in \mathbb{R}$$

$$\eta_3(u, v, w) = (u, v + \alpha w, w).$$

Consider a non-zero 1-jet $g = au + bv + cw$. If $a \neq 0$, then g is equivalent to u and its codimension is 0.

Suppose that $a = 0$. If $b \neq 0$, we use η_3 to set $c = 0$ and η_2 to set $b = \pm 1$. If $a = b = 0$ but $c \neq 0$ we can set $c = \pm 1$. Observe that $(u, v, w) \mapsto (u, v, -w)$ preserves X , so we can set $c = 1$. Thus, the orbits of submersions in the 1-jet space are $u, \pm v, w$.

• Consider the 1-jet $g = v$ (the results follow similarly for $g = -v$). Then $\xi_1(g) = 0$, $\xi_2(g) = 2v$ and $\xi_3(g) = 2w$, so for any integer $k \geq 2$, $\mathcal{M}_3^k \subset LR_1(X) \cdot g + \mathbb{R} \cdot \{u^k\} + \mathcal{M}_3^{k+1}$, that is, a complete k -transversal is given by $g = v + \lambda u^k$. Using η_2 we can set $\lambda = \pm 1$ if $\lambda \neq 0$ (if k is odd we can set $\lambda = 1$). For the germ $g = v \pm u^k$, we have $\xi_1(g) = \pm ku^{k-1}$, $\xi_2(g) = 2v$, $\xi_3(g) = 2w$. Now $\mathcal{M}_3^{k+1} \subset LR_1(X) \cdot g + \mathcal{M}_3^{k+2}$, so $v \pm u^k$ is k -determined. Its codimension is $k - 2$, and clearly, $v \pm u^k + a_{k-2}u^{k-2} + \dots + a_1 u_1$ is an $\mathcal{R}^+(X)$ -versal deformation.

• We consider now the 1-jet $g = w$. We have $\xi_1(g) = 0$, $\xi_2(g) = 3w$ and $\xi_3(g) = 3v^2$.

A complete 2-transversal is given by $g = w + \lambda_1 u^2 + \lambda_2 uv + \lambda_3 v^2$. We can consider g as a 1-parameter family of germs of functions parametrised by λ_3 . Then $\partial g / \partial \lambda_3 = v^2 \in \mathcal{E}_4 \cdot \{\mathcal{M}_3 \xi_1(g), \xi_2(g), \xi_3(g)\} + \mathcal{M}_3^3$, so by Proposition 3.4, g is equivalent to $w + \lambda_1 u^2 + \lambda_2 uv$. We proceed similarly to show that g is trivial along λ_2 if $\lambda_1 \neq 0$. Thus, if $\lambda_1 \neq 0$ we can take $g = w + \lambda_1 u^2$. We can now set $\lambda_1 = \pm 1$ by rescaling. For the germ $g = w \pm u^2$, we have $\xi_1(g) = \pm 2u$, $\xi_2(g) = 3w$, $\xi_3(g) = 3v^2$, so $\mathcal{M}_3^3 \subset LR_1(X) \cdot g + \mathcal{M}_3^4$, that is, g is 2-determined. The germ has codimension 1 and an $\mathcal{R}^+(X)$ -versal deformation is given by $g = w \pm u^2 + a_1 v$.

If $\lambda_1 = 0$ but $\lambda_2 \neq 0$ we can set $\lambda_2 = 1$ and consider $g = w + uv$. Then $\xi_1(g) = v$, $\xi_2(g) = 2uv + 3w$ and $\xi_3(g) = 2wu + 3v^2$, so $\mathcal{M}_3^3 \subset LR_1(X) \cdot g + \mathbb{R} \cdot \{u^3\} + \mathcal{M}_3^4$, that is, a complete 3-transversal is given by $g = w + uv + au^3$. Here a is a parameter modulus.

For $g = w + uv + au^3$ we have $\xi_1(g) = v + 3au^2$, $\xi_2(g) = 2uv + 3w$, $\xi_3(g) = 2uw + 3v^2$. Using the vectors $u^2 \xi_2(g) = 2u^3 v + 3u^2 w$, $u \xi_3(g) = 2u^2 w + 3uv^2$, $w \xi_1(g) = uv^2 + 3avu^3$ which are in $\mathcal{R}_1(X) \cdot g$, we get $u^2 w$, uv^2 and $u^3 v$ if $a \neq -4/27$. Then, using $u^3 \xi_1(g)$ we get u^5 if $a \neq 0$. Now using ξ_1 and ξ_2 we get all monomials divisible by v and w of degree 5 in $LR_1(X) \cdot g + \mathcal{M}_3^6$. Therefore g is 5-determined if $a \neq 0, -4/27$.

A complete 4-transversal of g is $\tilde{g} = g + \lambda u^4$. We use Mather's Lemma 3.6 with $G = \mathcal{R}^{(4)}(X)$ and $V = \{g + \lambda u^4, \lambda \in \mathbb{R}\}$. We have $T_{\tilde{g}} V = \mathbb{R} \cdot \{u^4\}$. The vectors $\xi_3(g)$, $v \xi_1(g)$, $u \xi_2(g)$ give uw , v^2 , $u^2 v$ in $T_{\tilde{g}} G \cdot \tilde{g} = J^4(LR(X) \cdot \tilde{g})$ for $a \neq -4/27$. Then $u^2 \xi_1(g)$ gives u^4 in $T_{\tilde{g}} G \cdot \tilde{g}$.

if $a \neq 0$. Therefore, $T_{\tilde{g}}V \subset T_{\tilde{g}}G.\tilde{g}$ for all $\tilde{g} \in V$ (provided that $a \neq 0, -4/27$). It is clear that $\dim T_{\tilde{g}}G.\tilde{g}$ is independent of \tilde{g} . Thus, by Mather's Lemma, $g + \lambda u^4$ is $\mathcal{R}(X)$ -equivalent to g , for all $\lambda \in \mathbb{R}$. It follows that g is 4-determined (provided that $a \neq 0, -4/27$). It has codimension 3 (the codimension of the stratum is 2) and an $\mathcal{R}^+(X)$ -versal deformation is given $g = w + uv + au^3 + a_2u^2 + a_1u$. \square

3.1. The geometry of functions on a cuspidal edge. We consider the \mathcal{A} -model cuspidal edge X parametrised by $f(x, y) = (x, y^2, y^3)$ and with equation $v^3 - w^2 = 0$. The tangential line at a singular point is parallel to $(1, 0, 0)$ and the tangent cone to X at a singular point is the plane $w = 0$.

Given a deformation $F : \mathbb{R}^3 \times \mathbb{R}^2, 0 \rightarrow \mathbb{R}$ of a germ g on X , we consider the family $G(x, y, a) = F(f(x, y), a)$ and define the discriminant of the family G as the set

$$\mathcal{D}_1(F) = \{(a, G(x, y, a)) \in \mathbb{R}^2 \times \mathbb{R} : \frac{\partial G}{\partial x} = \frac{\partial G}{\partial y} = 0 \text{ at } (x, y, a)\}$$

and the discriminant of the family G restricted to the singular set Σ as the set

$$\mathcal{D}_2(F) = \{(a, G(x, 0, a)) \in \mathbb{R}^2 \times \mathbb{R} : \frac{\partial G}{\partial x} = 0 \text{ at } (x, 0, a)\}.$$

It is not difficult to show that for two $P\text{-}\mathcal{R}^+(X)$ -equivalent deformations F_1 and F_2 the sets $\mathcal{D}_1(F_1)$ and $\mathcal{D}_1(F_2)$ are diffeomorphic and so are $\mathcal{D}_2(F_1)$ and $\mathcal{D}_2(F_2)$. Therefore, it is enough to compute the sets $\mathcal{D}_1(F)$ and $\mathcal{D}_2(F)$ for the deformations in Table 1.

- *The germ $g = u$.*

The fibre $g = 0$ is a plane transverse to both the tangential line and to the tangent cone to X . Here an $\mathcal{R}^+(X)$ -versal deformation is $F(u, v, w, a_1, a_2) = u$ and both $\mathcal{D}_1(F)$ and $\mathcal{D}_2(F)$ are the empty set.

- *The germs $g = \pm v \pm u^k$, $k = 2, 3, 4$.*

The fibre $g = 0$ is tangent to the tangential line of X at the origin but is transverse the tangent cone to X . The contact of the tangential line with the fibre $g = 0$ is measured by the singularities of $g(f(x, 0)) = \pm x^k$, so it is of type A_{k-1} .

(i) $k = 2$. Here an $\mathcal{R}^+(X)$ -versal deformation is $F(u, v, w, a_1, a_2) = \pm v \pm u^2$. Then $G(x, y, a_1, a_2) = \pm y^2 \pm x^2$, and both $\mathcal{D}_1(F)$ and $\mathcal{D}_2(F)$ are planes (Figure 1, left).

(ii) $k = 3$. We have $F(u, v, a_1, a_2) = \pm v + u^3 + a_1u$ and $G(x, y, a) = \pm y^2 + x^3 + a_1x$. Thus $\frac{\partial G}{\partial x} = \frac{\partial G}{\partial y} = 0$ when $y = 0$ and $a_1 = -3x^2$. The set $\mathcal{D}_1(F)$ is a surface parametrised by $(x, a_2) \mapsto (-3x^2, a_2, -2x^3)$, i.e., is a cuspidal edge. The set $\mathcal{D}_2(F)$ is also a cuspidal edge and coincides with $\mathcal{D}_1(F)$ (Figure 1, middle).

(iii) $k = 4$. Here $F(u, v, w, a_1, a_2) = \pm v \pm u^4 + a_2u^2 + a_1u$ and $G(x, y, a_1, a_2) = \pm y^2 \pm x^4 + a_2x^2 + a_1x$, so $\frac{\partial G}{\partial x} = \frac{\partial G}{\partial y} = 0$ when $y = 0$ and $a_1 = \mp 4x^3 - 2a_2x$. The set $\mathcal{D}_1(F)$ is a surface parametrised by $(x, a_2) \mapsto (\mp 4x^3 - 2a_2x, a_2, \mp 3x^4 - a_2x^2)$, which is a swallowtail surface. The set $\mathcal{D}_2(F)$ is also a swallowtail surface and coincides with $\mathcal{D}_1(F)$ (Figure 1, right).

- *The germ $g = w \pm u^2$.*

The tangent plane to the fibre $g = 0$ coincides with the tangent cone to X at the origin (and contains the tangential direction to X at that point). The contact of the fibre $g = 0$ with the tangential line is an ordinary one (of type A_1) as $g(f(x, 0)) = \pm x^2$.

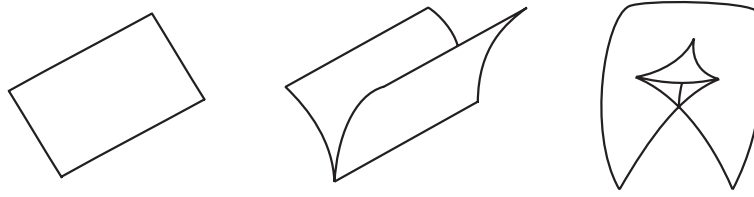


Fig. 1. The discriminants $\mathcal{D}_1(F)$ of versal deformations of $\pm v \pm u^k$, from left to right: $k = 2, 3, 4$. Here $\mathcal{D}_2(F)$ coincides with $\mathcal{D}_1(F)$.

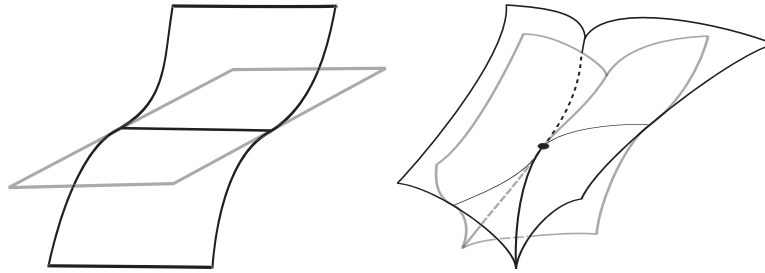


Fig. 2. Left: discriminant $\mathcal{D}_1(F)$ of a versal deformation of $w \pm u^2$, which is the union of two smooth surfaces having an A_2 -contact along a curve. Right: the discriminant $\mathcal{D}_1(F)$ of a versal deformation of $w + uv + au^3$, which is the union of two cuspidal edges. In both figures the discriminant $\mathcal{D}_2(F)$, which is a subset of $\mathcal{D}_1(F)$, is the surface in gray.

We have $F(u, v, a_1, a_2) = w + u^2 + a_1v$ and $G(x, y, a_1, a_2) = x^2 + y^3 + a_1y^2$, so $\frac{\partial G}{\partial x} = \frac{\partial G}{\partial y} = 0$ when $x = 0$ and $y(3y + a_1) = 0$. When $y = 0$ we get the plane $(a_1, a_2, 0)$ and for $3y + a_1 = 0$ we get a surface parametrised by $(x, a_2) \mapsto (-3y, a_2, -2y^3)$. The set $\mathcal{D}_1(F)$ is the union of these two surfaces, and these have an A_2 -contact along the a_2 -axis, see Figure 2 (left). The set $\mathcal{D}_2(F)$ is the plane $(a_1, a_2, 0)$.

- The germ $g = w + uv + au^3$, $a \neq 0$.

Here too, as in the previous case, the tangent plane to the fibre $g = 0$ coincides with the tangent cone to X at the origin. However, the contact of the fibre $g = 0$ with the tangential line is of order 3 as $g(x, 0, 0) = ax^3$.

We have $F(u, v, w, a_1, a_2) = w + uv + au^3 + a_2u^2 + a_1u$ and $G(x, y, a_1, a_2) = xy^2 + y^3 + ax^3 + a_2x^2 + a_1x$. Differentiating we get

$$\begin{aligned} \frac{\partial G}{\partial x} &= y^2 + 3ax^2 + 2a_2x + a_1 \\ \frac{\partial G}{\partial y} &= 2xy + 3y^2. \end{aligned}$$

We have $\frac{\partial G}{\partial y} = 0$ when $y = 0$ or $y = -(2/3)x$. Substituting in $\frac{\partial G}{\partial x} = 0$ gives $\mathcal{D}_1(F)$ as the union of two surfaces parametrised by

$$(a_2, x) \mapsto (-3ax^2 - 2a_2x, a_2, -2ax^3 - a_2x^2)$$

and

$$(a_2, x) \mapsto \left(-\left(\frac{4}{9} + 3a \right) x^2 - 2a_2x, a_2, -\left(\frac{8}{27} + 2a \right) x^3 - a_2x^2 \right).$$

Both these surfaces are cuspidal edges and are as in Figure 2 (right). The set $\mathcal{D}_2(F)$ coincides with the first cuspidal edge.

3.2. Contact of a geometric cuspidal edge with planes. The family of height functions $H : M \times S^2 \rightarrow \mathbb{R}$ on M is given by $H((x, y), \mathbf{v}) = H_{\mathbf{v}}(x, y) = \phi(x, y) \cdot \mathbf{v}$. The height function $H_{\mathbf{v}}$ on M along a fixed direction \mathbf{v} measures the contact of M at p with the plane $\pi_{\mathbf{v}}$ through p and orthogonal to \mathbf{v} . The contact of M with $\pi_{\mathbf{v}}$ is described by that of the fibre $g = 0$ with the model cuspidal edge X , with g as in Theorem 3.7. Following the transversality theorem in the Appendix of [8], for a generic cuspidal-edge, the height functions $H_{\mathbf{v}}$, for any $\mathbf{v} \in S^2$, can only have singularities of $\mathcal{R}_e^+(X)$ -codimension ≤ 2 (of the stratum) at any point on the cuspidal edge. We shall take M parametrised as in (1) and write $\mathbf{v} = (v_1, v_2, v_3)$. Then,

$$H_{\mathbf{v}}(x, y) = H((x, y), \mathbf{v}) = xv_1 + (a(x) + \frac{1}{2}y^2)v_2 + (b_1(x) + y^2b_2(x) + y^3b_3(x, y))v_3.$$

The function $H_{\mathbf{v}}$ is singular at the origin if and only if $v_1 = 0$, that is, if and only if the plane $\pi_{\mathbf{v}}$ contains the tangential direction to M at the origin.

When $\pi_{\mathbf{v}}$ is transverse to the tangential direction to M at the origin, the contact of M with $\pi_{\mathbf{v}}$ at the origin is the same as that of the zero fibre of $g = u$ with the model cuspidal edge X .

Suppose that the plane $\pi_{\mathbf{v}}$ is a member of the pencil of planes that contains the tangential direction to M at the origin (in particular, $\pi_{\mathbf{v}}$ is a tangent plane of the curve Σ). If $\pi_{\mathbf{v}}$ is not the tangent cone to M at the origin, then the contact of a generic M with $\pi_{\mathbf{v}}$ is the same as that of the zero fibre of $g = \pm v \pm u^k$, $k = 2, 3, 4$ with the model cuspidal edge X . The integer k is determined by the contact of $\pi_{\mathbf{v}}$ with the singular set Σ (see §3.1). The restriction of $H_{\mathbf{v}}$ to Σ is given by

$$H_{\mathbf{v}}(x, 0) = \frac{1}{2}(a_{20}v_2 + b_{20}v_3)x^2 + \frac{1}{6}(a_{30}v_2 + b_{30}v_3)x^3 + \frac{1}{24}(a_{40}v_2 + b_{40}v_3)x^4 + O(5).$$

Therefore, the plane $\pi_{\mathbf{v}}$ has an A_k , $k = 1, 2, 3$, contact with Σ if and only if

$$\begin{aligned} A_1 : & \quad v_2a_{20} + v_3b_{20} \neq 0; \\ A_2 : & \quad v_2a_{20} + v_3b_{20} = 0, \quad a_{20}b_{30} - a_{30}b_{20} \neq 0; \\ A_3 : & \quad v_2a_{20} + v_3b_{20} = 0, \quad a_{20}b_{30} - a_{30}b_{20} = 0, \quad a_{40}b_{20} - a_{20}b_{40} \neq 0. \end{aligned}$$

Geometrically, this mean that the plane $\pi_{\mathbf{v}}$ has an A_k , $k = 1, 2, 3$, contact with Σ if and only if

$$\begin{aligned} A_1 : & \quad \pi_{\mathbf{v}} \text{ is not the osculating plane of } \Sigma; \\ A_2 : & \quad \pi_{\mathbf{v}} \text{ is the osculating plane of } \Sigma, \quad \tau_{\Sigma}(0) \neq 0; \\ A_3 : & \quad \pi_{\mathbf{v}} \text{ is the osculating plane of } \Sigma, \quad \tau_{\Sigma}(0) = 0, \quad \tau'_{\Sigma}(0) \neq 0. \end{aligned}$$

If the plane $\pi_{\mathbf{v}}$ coincides with the tangent cone to M at the origin (i.e., $\mathbf{v} = (0, 0, 1)$) but is not the osculating plane of Σ (i.e., $\kappa_n(0) = b_{20} \neq 0$), then the contact of M with $\pi_{\mathbf{v}}$ is the same as that of the zero fibre of $g = w \pm u^2$ with the model cuspidal edge X , that is, the height function has an A_3 -singularity.

When $\pi_{\mathbf{v}}$ is the tangent cone to M and coincides with the osculating plane of Σ ($\kappa_n(0) = b_{20} = 0$) but $\tau_{\Sigma}(0) \neq 0$ (i.e., $\kappa_t(0) = b_{30} \neq 0$) its contact with M is described by the germ $g = w + uv + au^3$ with the model cuspidal edge X . Here, the corresponding height function has a D_4 -singularity. (Compare with Theorem 2.11 in [17] and Lemma 4.2 in [24].) We observe that the case when the tangent cone to M and the osculating plane of Σ coincides at

a point where $\tau_\Sigma(0) = 0$ is not generic.

We have the sets

$$\mathcal{D}_1(H) = \{(\mathbf{v}, H_{\mathbf{v}}(x, y)) \in S^2 \times \mathbb{R} : \frac{\partial H_{\mathbf{v}}}{\partial x} = \frac{\partial H_{\mathbf{v}}}{\partial y} = 0 \text{ at } (x, y, \mathbf{v})\}$$

and

$$\mathcal{D}_2(H) = \{(\mathbf{v}, H_{\mathbf{v}}(x, 0)) \in S^2 \times \mathbb{R} : \frac{\partial H_{\mathbf{v}}}{\partial x} = 0 \text{ at } (x, 0, \mathbf{v})\}.$$

If $\pi_{\mathbf{v}}$ is a member of the pencil containing the tangential direction of M but is not the tangent cone to M , then the set $\mathcal{D}_1(H)$ coincides with $\mathcal{D}_2(H)$ and describes locally the dual of the curve Σ . When $\pi_{\mathbf{v}}$ is the tangent cone to M , then the set $\mathcal{D}_1(H)$ consists of two components. One of them is $\mathcal{D}_2(H)$ (the dual of Σ) and the other is the *proper dual* of M which is the surface consisting of the tangent planes to M away from points on Σ together with their limits at points on Σ , i.e., the tangent cones at points on Σ .

If the contact of M with $\pi_{\mathbf{v}}$ is described by that of the fibre $g = 0$ with the model cuspidal edge X , with g as in Theorem 3.7, then $\mathcal{D}_1(H)$ (resp. $\mathcal{D}_2(H)$) is diffeomorphic to $\mathcal{D}_1(F)$ (resp. $\mathcal{D}_2(F)$), where F is an $\mathcal{R}^+(X)$ -versal deformation of g with 2-parameters. In particular, the calculations and figures in §3.1 give the models, up to diffeomorphisms, of $\mathcal{D}_1(H)$ and $\mathcal{D}_2(H)$. We have thus the following result.

Proposition 3.8. *Let M be a generic cuspidal edge in \mathbb{R}^3 . Then any height function on M has locally one of the singularities modeled by the submersions in Table 1. The proper dual of M together with the dual of its singular curve Σ are as in Figure 2, left, when the tangent cone to M is distinct from the osculating plane to Σ and as Figure 2, right, otherwise.*

4. Orthogonal projections of a cuspidal edge

The family of orthogonal projections in \mathbb{R}^3 is given by

$$\begin{aligned} \Pi : \mathbb{R}^3 \times S^2 &\rightarrow TS^2 \\ (p, \mathbf{v}) &\mapsto (\mathbf{v}, \Pi_{\mathbf{v}}(p)) \end{aligned}$$

where $\Pi_{\mathbf{v}}(p) = p - (p \cdot \mathbf{v})\mathbf{v}$. Given a surface M , we denote by P the restriction of Π to M . Thus, for M parametrised by ϕ , the family of orthogonal projections $P : U \times S^2 \rightarrow TS^2$ is given by

$$P((x, y), \mathbf{v}) = (\mathbf{v}, P_{\mathbf{v}}(x, y)),$$

with $P_{\mathbf{v}}(x, y) = \Pi_{\mathbf{v}}(\phi(x, y)) = \phi(x, y) - (\phi(x, y) \cdot \mathbf{v})\mathbf{v}$. The map $P_{\mathbf{v}}$ is locally a map-germ from the plane to the plane and measures the contact of M with lines parallel to \mathbf{v} .

We take M parametrised as in (1). Consider, for example, the projection along the tangential direction $\mathbf{v} = (0, 1, 0)$. We have $P_{\mathbf{v}}(x, y) = (x, b_1(x) + y^2 b_2(x) + y^3 b_3(x, y))$. If $\kappa_t = b_{12} = 0$ and $\kappa'_t = b_{22} \neq 0$, the singularity of $P_{\mathbf{v}}$ at the origin is \mathcal{A} -equivalent to $(x, y^3 - x^4 y)$ and has \mathcal{A}_e -codimension 3 (see §4.1 for even higher \mathcal{A}_e -codimension cases). Thus, it cannot be \mathcal{A}_e -versally unfolded by the family P . For this reason, the group \mathcal{A} is not very useful for describing the singularities of the projections of M and the way they bifurcate as the direction of projection changes in S^2 . We follow here the same approach as that for the contact of the cuspidal edge with planes. The projections are germs of submersions, so we fix the

\mathcal{A} -model X of the cuspidal edge and consider the action of the group ${}_X\mathcal{A} = \mathcal{R}(X) \times \mathcal{L}$ on $\mathcal{M}_3.\mathcal{E}(3, 2)$. We classify germs of submersions g in $\mathcal{M}_3.\mathcal{E}(3, 2)$ of ${}_X\mathcal{A}_e$ -codimension $d_e(f, {}_X\mathcal{A}) = \dim_{\mathbb{R}}(\mathcal{E}(3, 2)/L_X\mathcal{A}_e \cdot f) \leq 2$. We need the following results from [5] and [6] adapted to our group, where

$$\begin{aligned} L_X\mathcal{A}_1 \cdot g &= L\mathcal{R}_1(X) \cdot g + g^*(\mathcal{M}_3^2) \cdot \{e_1, e_2\}, \\ L_X\mathcal{K} \cdot g &= L\mathcal{R}(X) \cdot g + g^*(\mathcal{M}_3) \cdot \{e_1, e_2\}. \end{aligned}$$

Theorem 4.1 ([5]). *Let $g : \mathbb{R}^3, 0 \rightarrow \mathbb{R}^2, 0$ be a smooth germ and h_1, \dots, h_r be homogeneous maps of degree $k+1$ with the property that*

$$\mathcal{M}_3^{k+1}.\mathcal{E}(3, 2) \subset L_X\mathcal{A}_1 \cdot g + \mathbb{R} \cdot \{h_1, \dots, h_r\} + \mathcal{M}_3^{k+2}.\mathcal{E}(3, 2).$$

Then any germ h with $j^k h(0) = j^k f(0)$ is ${}_X\mathcal{A}_1$ -equivalent to a germ of the form $g(x) + \sum_{i=1}^r u_i h_i(x) + \phi(x)$, where $\phi(x) \in \mathcal{M}_3^{k+2}.\mathcal{E}(3, 2)$. The vector subspace $\mathbb{R} \cdot \{h_1, \dots, h_r\}$ is called a complete $(k+1)$ - ${}_X\mathcal{A}$ -transversal of g .

Theorem 4.2 ([6]). *If g satisfies*

$$\begin{aligned} \mathcal{M}_3^l.\mathcal{E}(3, 2) &\subset L_X\mathcal{K} \cdot g \\ \mathcal{M}_3^{k+1}.\mathcal{E}(3, 2) &\subset L_X\mathcal{A}_1 \cdot g + \mathcal{M}_3^{l+k+1}.\mathcal{E}(3, 2) \end{aligned}$$

then g is k - ${}_X\mathcal{A}$ -determined.

We can now state the classification result for submersions in $\mathcal{M}_3.\mathcal{E}(3, 2)$ of ${}_X\mathcal{A}_e$ -codimension ≤ 2 (of the stratum).

Theorem 4.3. *Let X be the germ of the \mathcal{A} -model of the cuspidal edge parametrised by $f(x, y, z) = (x, y^2, y^3)$. Denote by (u, v, w) the coordinates in the target. Then any germ of a submersion in $\mathcal{M}_3.\mathcal{E}(3, 2)$ of ${}_X\mathcal{A}_e$ -codimension ≤ 2 is ${}_X\mathcal{A}$ -equivalent to one of the germs in Table 2.*

Table 2. ${}_X\mathcal{A}$ -finitely determined germs of ${}_X\mathcal{A}_e$ -codimension ≤ 2 .

| Name | Normal form | $d_e(f, {}_X\mathcal{A})$ | ${}_X\mathcal{A}_e$ -versal deformation |
|--------|--|---------------------------|---|
| Type 1 | (u, v) | 0 | (u, v) |
| Type 2 | $(u, w + uv)$ | 0 | $(u, w + uv)$ |
| Type 3 | $(u, w + u^2v)$ | 1 | $(u, w + u^2v + a_1v)$ |
| Type 4 | $(u, w + u^3v)$ | 2 | $(u, w + u^3v + a_2uv + a_1v)$ |
| Type 5 | $(v + u^3, w + u^2)$ | 1 | $(v + u^3 + a_1u, w + u^2)$ |
| Type 6 | $(v + u^5, w + u^2)$ | 2 | $(v + u^5 + a_2u^3 + a_1u, w + u^2)$ |
| Type 7 | $g_7 = (v + au^2 \pm u^4, w + uv + bu^3 + P),$ $P = cu^4 + du^5 + eu^6$ | $2^{(*)}$ | $g_7 + (0, a_1u + a_2u^2)$ |

(*): the codimension is of the stratum; a, b, c, d, e are moduli and are in the complement of some algebraic subsets of \mathbb{R}^5 .

Proof. We follow the complete transversal technique and classify germs of submersions inductively of the jet level. Consider the 1-jet $g = (a_1u + b_1v + c_1w, a_2u + b_2v + c_2w)$. If $a_1 \neq 0$ or $a_2 \neq 0$ then g is equivalent to $(u, av + bw)$, with $a \neq 0$ or $b \neq 0$ (g is a germ of a submersion). For $g = (u, av + bw)$, $\xi_1(g) = (1, 0)$, $\xi_2(g) = (0, 2av + 3bw)$, $j^1\xi_3(g) = (0, 2aw)$, so if $a \neq 0$, by applying Mather's Lemma, we get g equivalent to (u, v) , otherwise it is equivalent to (u, w) . If $a_1 = a_2 = 0$, then changes of coordinates in the target give g

equivalent to (v, w) . Thus, we have three orbits of submersions in the 1-jet space represented by (u, v) , (u, w) , (v, w) . The germ (u, v) is 1-determined and is stable.

• For $g = (u, w)$, we have $\xi_1(g) = (1, 0)$, $\xi_2(g) = (0, w)$, $\xi_3(g) = (0, 3v^2)$. Using these vectors and the left group, we can show that a complete $(k + 1)$ -transversal is $(u, w + \lambda u^k v)$, $k \geq 1$. We have two orbits in the $(k + 1)$ -jet space, namely $(u, w + u^k v)$ and (u, w) . For $g = (u, w + u^k v)$, we have $\xi_1(g) = (1, ku^{k-1}v)$, $\xi_2(g) = (0, 3w + 2u^k v)$, $\xi_3(g) = (0, 3v^2 + 2u^k w)$. Using the above vectors and the left group, we can show that $\mathcal{M}_3^2 \cdot \mathcal{E}(3, 2) \subset L_X \mathcal{K} \cdot g$. To prove that the germ is $k + 1$ -determined we need to prove that

$$(2) \quad \mathcal{M}_3^{k+2} \cdot \mathcal{E}(3, 2) \subset L_X \mathcal{A}_1 \cdot g + \mathcal{M}_3^{k+4} \cdot \mathcal{E}(3, 2).$$

For this, we first show that all monomials of degree $k + 3$ are in the right hand side of (2). Using ξ_i , $i = 1, 2, 3$, we show that all the monomials of degree $k + 3$ of the form $(P(u, v, w), 0)$, $(0, wP(u, v, w))$ and $(0, v^2 P(u, v, w))$ are in there. We use the left group to show that $(0, u^{k+3})$ is also in there. If we write $g = (g_1, g_2)$, then $(0, g_1^i g_2) = (0, u^i w + u^{k+i} v)$ and $u^i \xi_2(g) = (0, 3u^i w + 2u^{k+i} v)$. For $i \geq 1$ these vectors are in $L_X \mathcal{A}_1 \cdot g$, so $(0, u^{k+2} v)$ is in the right hand side of (2). We proceed similarly for the monomials of degree $k + 2$ working now with vectors in $L_X \mathcal{A}_1 \cdot g$ modulo elements in $\mathcal{M}_3^{k+3} \cdot \mathcal{E}(3, 2)$ to get all monomials of degree $k + 2$ in the right hand side of (2). Therefore, (2) holds. The germ g has ${}_X \mathcal{A}_e$ -codimension $k - 1$ and an ${}_X \mathcal{A}_e$ -versal unfolding is $(u, w + u^k v + a_{k-1} u^{k-1} v + \dots a_1 u v)$.

• For $g = (v, w)$, we have $\xi_1(g) = (0, 0)$, $\xi_2(g) = (2v, 3w)$, $\xi_3(g) = (2w, 3v^2)$ and a complete 2-transversal is given by $g = (v + a_1 u v + a_2 u^2, w + b_1 u v + b_2 u^2)$. Then $\xi_1(g) = (a_1 v + 2a_2 u, b_1 v + 2b_2 u)$, $\xi_2(g) = (2v + 2a_1 u v, 3w + 2b_1 u v)$, $\xi_3(g) = (2w + 2a_1 u w, 3v^2 + 2b_1 u w)$. Now $j^2 w \xi_1(g) = (a_1 v w + 2a_2 u w, b_1 v w + 2b_2 u w)$ and $j^2 u \xi_3(g) = (2u w, 0)$ and we have $(v w, 0)$ and $(0, v w)$ from the left group in the 2-jet of the ${}_X \mathcal{A}$ tangent space to the orbit of g , so if $b_2 \neq 0$, we obtain $(0, u w)$. From this and $j^2 u \xi_2(g) = (2u v, 3u w)$, we also get $(u v, 0)$. Then $j^2 v \xi_1(g) = (a_1 v^2 + 2a_2 u v, b_1 v^2 + 2b_2 u v)$ together with $(v^2, 0)$ and $(0, v^2)$ from the left group also gives $(0, u v)$ if $b_2 \neq 0$. Therefore, by Mather's Lemma g is equivalent to $(v + a u^2, w + b u^2)$, with $b \neq 0$. Using the vectors $(w + b u^2, 0)$, $\xi_3(g) = (2w, 3v^2)$ and $(0, v^2)$ from the left group, shows that g is equivalent to $(v, w + b u^2)$ if $b \neq 0$. We can then set $b = 1$ by changes of scales. If $b_2 = 0$ and $b_1 \neq 0$, then g is equivalent to $(v + a u^2, w + u v)$, with a a parameter modulus. If $b_1 = b_2 = 0$, the orbits are $(v \pm u^2, w)$, $(v + u v, w)$ and (v, w) and all yield germs of submersions of codimension (of the stratum) greater than 2. Thus, the 2 jets to consider are $(v, w + u^2)$ and $(v + a u^2, w + u v)$.

Consider the germ $g = (v, w + u^2)$. Then $\xi_1(g) = (0, 2u)$, $\xi_2(g) = (2v, 3w)$ and $\xi_3(g) = (2w, 3v^2)$. Using these vectors and those from the left group we can show that a complete 3-transversal is $g = (v + \lambda u^3, w + u^2)$ and the orbits in the 3-jet space are $(v + u^3, w + u^2)$ and $(v, w + u^2)$. The germ $(v + u^3, w + u^2)$ is 3-determined and has codimension 1. An ${}_X \mathcal{A}_e$ -versal unfolding is given by $(v + u^3 + a_1 u, w + u^2)$.

The complete 4-transversal for $(v, w + u^2)$ is empty and the orbits in the 5-jet are $(v + u^5, w + u^2)$ and $(v, w + u^2)$. The germ $(v + u^5, w + u^2)$ is 5-determined and has codimension 2. An ${}_X \mathcal{A}_e$ -versal unfolding is given by $(v + u^5 + a_2 u^3 + a_1 u, w + u^2)$.

For the 2-jet $(v + a u^2, w + u v)$ a complete 3-transversal is given by $g = (v + a u^2 + \lambda_1 u^3, w + u v + \lambda_2 u^3)$. Using Mather's Lemma, it can be shown that g is equivalent to $g = (v + a u^2, w + u v + b u^3)$, where b is also a modulus. A complete 4-transversal is $g = (v + a u^2 \pm u^4, w +$

$uv + bu^3 + cu^4$). The complete 5-transversal is not empty and the orbits in the 6-jet space can be parametrised by $g_7 = (v + au^2 \pm u^4, w + uv + bu^3 + cu^4 + du^5 + eu^6)$. We can then show that the germ g_7 is 6-determined provided the moduli are not in the zero set of some polynomial. The codimension of the stratum of g_7 is 2 and an ${}_X\mathcal{A}_e$ -versal unfolding is given by $g_7 + (0, a_1u + a_2u^2)$. \square

REMARK 4.4. The computations for obtaining the complete transversals and checking finite determinacy for the case Type 7 in the proof of Theorem 4.3 are carried out using the computer package “Transversal” developed by Kirk ([15]).

4.1. Apparent contour of a cuspidal edge. The singular set of an orthogonal projection of a smooth surface in \mathbb{R}^3 along a direction \mathbf{v} is the set of point where \mathbf{v} is tangent to the surface and is called the *contour generator*. The image of the contour generator by the projection in the direction \mathbf{v} is called the *apparent contour (profile)* of the surface along the directions \mathbf{v} . (See for example [12, 20] and also [10, 14, 16] for more on apparent contours of smooth surfaces, [3] for surfaces with boundary, [23] for those with creases and corners, [10] for applications to images (involving shade, shadow and contours) and [1, 26] for those of a surface with a cross-cap singularity.)

For a geometric cuspidal edge M , the projection is always singular along the singular curve Σ , so Σ is always part of the contour generator and its image is part of the apparent contour of M along \mathbf{v} . We call the *proper apparent contour (profile)* of M the projection of the closure of the set of points where \mathbf{v} is tangent to M at its regular points. We seek to describe the apparent contour of M and how it changes as the direction of projection changes locally in S^2 .

Theorem 4.5. *The bifurcations on the proper apparent contour of M together with those of the projection of the singular set of M are, up to diffeomorphisms, those in the following figures:*

- Type 2: Figure 3
- Type 3: Figure 4
- Type 4: Figure 5
- Type 5: Figure 6
- Type 6: Figure 7
- Type 7: Figures 9, 10, 11, 12, 13 for some cases.

For Type 1 singularities, the proper apparent contour is empty and the projection of the singular set is a regular curve.

Proof. The apparent contour is the discriminant of the projection (that is, the image of its singular set). For a generic surface, the family of projections is an ${}_X\mathcal{A}_e$ -versal family of the singularities of its members. Therefore, the diffeomorphism type of the bifurcations of the apparent contour can be obtained by considering the bifurcations of the discriminants in the ${}_X\mathcal{A}_e$ -versal families restricted to X in Theorem 4.3. We treat each case in Table 2 separately.

- **Type 1:** The germ $g = (u, v)$. We denote by h the composite of g with the parametrisation $f(x, y) = (x, y^2, y^3)$ of X . Then $h(x, y) = (x, y^2)$ which has a singularity of \mathcal{A} -type fold. The critical set of h is the x -axis, i.e., is the singular set of X , and the discriminant is a regular

curve.

- The germ $g = (u, w + u^k v)$, $k = 1, 2, 3$. Here we have $h(x, y) = (x, y^3 + x^k y^2)$ and its singular set is given by $y(3y + 2x^k) = 0$. It has two components, one of which ($y = 0$) is the singular set of X . The other component (the proper contour generator) is a smooth curve and has k -point contact with the singular set of X .

Type 2: $k = 1$. The germ $h(x, y) = (x, y^3 + xy^2)$ has a singularity of \mathcal{A} -type beaks (which is of \mathcal{A}_e -codimension 1 but g is ${}_X\mathcal{A}_e$ -stable). The discriminant is the union of the two curves $(x, 0)$ and $(x, (4/27)x^3)$ which have 3-point contact at the origin (Figure 3).

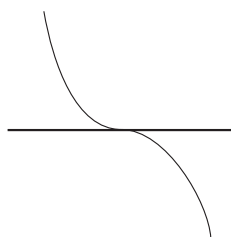


Fig. 3. Proper apparent contour (thin) and the projection of the singular set (thick) of M at an ${}_X\mathcal{A}$ -singularity of Type 2.

Type 3: $k = 2$. We consider the versal deformation $g = (u, w + u^2 v + a_1 uv)$ with parameter a_1 , so $h(x, y) = (x, y^3 + x^2 y^2 + a_1 y^2)$. (When $a_1 = 0$, h is \mathcal{A} -equivalent to $(x, y^3 - x^4 y)$ which is a singularity of \mathcal{A} -type 4_4 , see [20].) For a_1 fixed, the critical set is given by $y(3y + 2x^2 + 2a_1) = 0$ and consists of two curves $y = 0$ and $y = -(2/3)(x^2 + a_1)$. The discriminant is the union of the two curves $(x, 0)$ and $(x, (4/27)(x^2 + a_1)^3)$. See Figure 4 for the bifurcations in these curves as a_1 varies near zero.

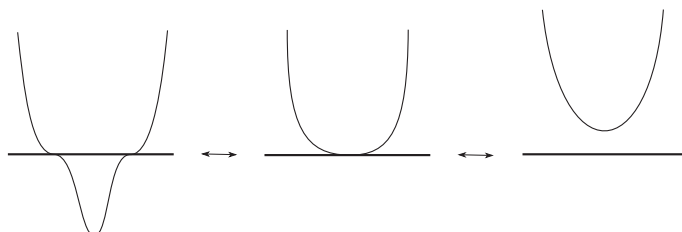


Fig. 4. Bifurcations in generic 1-parameter families of the proper apparent contour (thin) and of the projection of the singular set (thick) of M at an ${}_X\mathcal{A}$ -singularity of Type 3.

Type 4: $k = 3$: We consider the versal deformation $g = (u, w + u^3 v + a_2 uv + a_1 v)$ with parameters a_1, a_2 , so $h(x, y) = (x, y^3 + x^3 y^2 + a_2 xy^2 + a_1 y^2)$. (At $a_1 = a_2 = 0$, f is \mathcal{A} -equivalent to $(x, y^3 - x^6 y)$ which is a singularity of \mathcal{A} -type 4_6 .) The critical set is given by $y(3y + 2(x^3 + a_2 x + a_1)) = 0$. The family $x^3 + a_2 x + a_1$ is a \mathcal{K} -versal deformation of the A_2 -singularity, so the bifurcations in the critical set are as in Figure 5 (left) and those in the discriminant are as in Figure 5 (right). Singularities of Type 3 occur when (a_1, a_2) are on the cusp curve $27a_1^2 + 4a_2^3 = 0$ (middle figures in Figure 5).

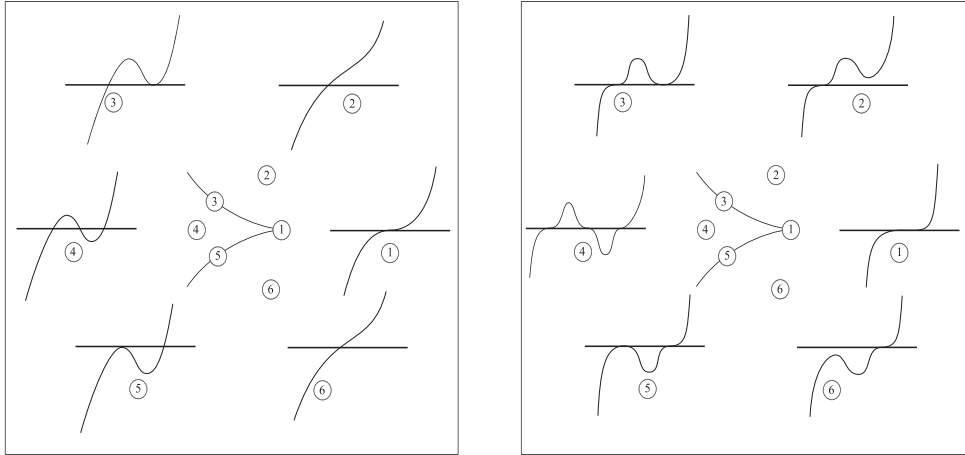


Fig. 5. Bifurcations in generic 2-parameter families of the critical set (left), and of the proper apparent contour (thin) and of the projection of the singular set (thick) of M (right) at an $x\mathcal{A}$ -singularity of Type 4.

• Type 5: Here we have a versal family $g = (v + u^3 + a_1u, w + u^2)$, so $h(x, y) = (y^2 + x^3 + a_1x, y^3 + x^2)$. (When $a_1 = a_2 = 0$, f has an \mathcal{A} -singularity of type $I_{2,2}^{1,1}$, see [21].) The critical set is given by $y(4x - 3y(3x^2 + a_1)) = 0$ and is the union of two transverse curves. The image of the curve $y = 0$ is the \mathcal{A}_e -versal family $(x^3 + a_1x, x^2)$ of a cusp curve (Figure 6, thick curve). The image of the other branch is a cusp when $a_1 = 0$, and when $a_1 \neq 0$, we write $y = 4x/(3(3x^2 + a_1))$ so its image can be parametrised by

$$\left(\frac{16}{9} \frac{x^2}{(3x^2 + a_1)^2} + x^3 + a_1x, \frac{64}{27} \frac{x^3}{(3x^2 + a_1)^3} + x^2\right).$$

A short calculation shows that it has always a cusp singularity near the origin for all values of $a_1 \neq 0$ near zero. The origin is a Type 2 singularity for any $a_1 \neq 0$; see Figure 6.



Fig. 6. Bifurcations in generic 1-parameter families of the proper apparent contour (thin) and of the projection of the singular set (thick) of M at an $x\mathcal{A}$ -singularity of Type 5.

• Type 6: The versal family $g = (v + u^5 + a_2u^3 + a_1u, w + u^2)$ gives $h(x, y) = (y^2 + x^5 + a_2x^3 + a_1x, y^3 + x^2)$ (which has a singularity of \mathcal{A} -type $I_{2,2}^{1,2}$ at $a_1 = a_2 = 0$). The critical set is given by $y(4x - 3y(a_1 + 3a_2x^2 + 5x^4)) = 0$ and consists of two transverse curves for any (a_1, a_2) near the origin. The image of $y = 0$ is the \mathcal{A}_e -versal family $(x^5 + a_2x^3 + a_1x, x^2)$ of the ramphoid cusp curve. The \mathcal{A}_e -deformations in this family are obtained in [13, 25] and are as in Figure 7, thick curves. One can show that there are no other local or multi-local singularities appearing in the deformation.

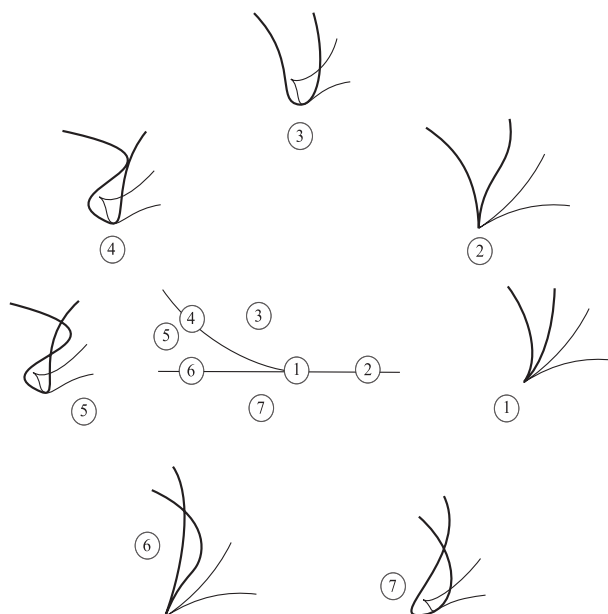


Fig. 7. Stratification of the parameter space (central figure) and bifurcations in generic 2-parameter families of the proper apparent contour (thin) and of the projection of the singular set (thick) of M at an $x\mathcal{A}$ -singularity of Type 6.

• Type 7: The versal family $(v + au^2 \pm u^4, w + uv + bu^3 + cu^4 + du^5 + eu^6 + a_2u^2 + a_1u)$ gives $h(x, y) = (y^2 + ax^2 \pm x^4, y^3 + xy^2 + bx^3 + cx^4 + dx^5 + ex^6 + a_2x^2 + a_1x)$ (which has a non-simple corank 2 singularity when $a_1 = a_2 = 0$; these are yet to be classified). We shall stratify the parameter space (a_1, a_2) near the origin by the loci of codimension 2,1,0 local and multi-local singularities of h . The stratification depends on the five moduli of g_7 in Table 2. However, as shown by the calculations below, the configuration of the strata (up to homeomorphism $\mathbb{R}^2, 0 \rightarrow \mathbb{R}^2, 0$) depends only on the two moduli a and b . We also obtain a (partial) stratification of the (a, b) plane into strata where the configuration of the bifurcation set of h is constant.

The singular set of h is given by

$$y(a_1 + 2a_2x - (2a - 3b)x^2 - 3axy + y^2 + 4cx^3 + (5d \mp 4)dx^4 \mp 6yx^3 + 6ex^5) = 0.$$

It consists of the singular set of the cuspidal edge $y = 0$ and another component given by the function

$$S_{(a_1, a_2)}(x, y) = a_1 + 2a_2x - (2a - 3b)x^2 - 3axy + y^2 + 4cx^3 + (5d \mp 4)dx^4 \mp 6yx^3 + 6ex^5.$$

The image of $y = 0$ gives an \mathcal{A}_e -versal family

$$(ax^2 \pm x^4, bx^3 + cx^4 + dx^5 + ex^6 + a_2x^2 + a_1x)$$

of a cusp curve. (We require $a \neq 0$ and $b \neq 0$ which are also conditions for finite determinacy of the germ g_7 in Table 2. We observe that we get a self-intersection in the image of $y = 0$ if and only if $a_1b < 0$.)

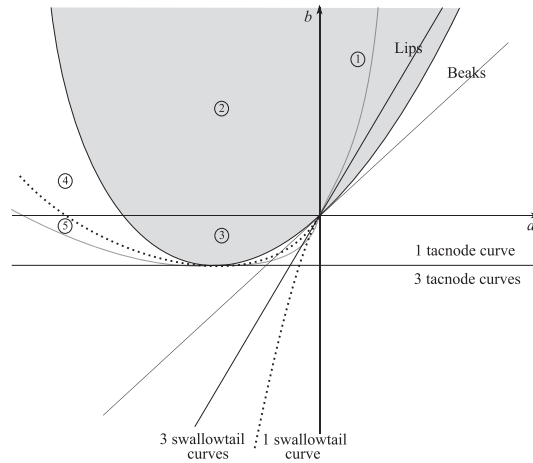


Fig.8. A (partial) stratification of the (a, b) -plane.

The lips/beaks stratum

The function $S_{(a_1, a_2)}(x, y)$ has a Morse singularity at the origin if and only if $9a^2 + 8a - 12b \neq 0$. We obtain a stratum in the (a, b) -plane given by the curve

$$(3) \quad 9a^2 + 8a - 12b = 0,$$

where the singularity of $S_{(0,0)}$ is more degenerate. The parabola (3) splits the (a, b) -plane into two regions. For (a, b) inside (resp. outside) the parabola, we have a birth of a lips (resp. beaks) singularity on one of the regular sheets of the cuspidal edge (see Figure 8). We call the singularities of Type 7 lips (resp. beaks) type if lips (resp. beaks) singularities appear in its bifurcations.

The lips/beaks stratum in the (a_1, a_2) -parameter space is given by the set of parameters (a_1, a_2) for which there exists (x, y) near the origin such that $S_{(a_1, a_2)}(x, y) = 0$ and the function $S_{(a_1, a_2)}$ has a Morse singularity at (x, y) . Eliminating variables, we find that the lips/beaks stratum is a regular curve parametrised by

$$(4) \quad a_1 = -\frac{4}{9a^2 + 8a - 12b} a_2^2 + O_3,$$

where O_3 (here and in the rest of the paper) is a family of smooth functions in a_2 depending smoothly on a, b, c, d, e and has a zero 2-jet as a function in a_2 .

Swallowtail stratum

Using the recognition criteria in [22], we find the stratum where swallowtail singularities occur is given by

$$(5) \quad a_1 = \frac{4(3a^2 + (3b - 4a)\alpha - \alpha^3)\alpha}{9(a^2 + 2(b - a)\alpha - \alpha^2 a)^2} a_2^2 + O_3,$$

where α is a solution of the cubic equation

$$P(\alpha) = 2(a - b)\alpha^3 - 3a^2\alpha^2 - a^3 = 0.$$

The discriminant of P is $\delta_P = a^3 + (a - b)^2$. It is a cusp curve tangent to the lips/beaks parabola at $(-\frac{4}{9}, -\frac{4}{27})$ where both curves have a horizontal tangent (dotted curve in Figure

8). There are thus three swallowtail curves in the bifurcation set of h for (a, b) inside the cusp curve $\delta_P = 0$ and one swallowtail curve for (a, b) outside this curve (see Figure 8). In particular, when lips singularities occur on the profile, only one swallowtail curve is present in the bifurcation set of h . From (5) we have two additional strata in the (a, b) plane given as follows:

(i) the swallowtail curve is inflectional, so α is also a root of $3a^2 + (3b - 4a)\alpha - \alpha^3$. Calculating the resultant of this polynomial and P we get $243a^4 + 4(4a - 3b)^3 = 0$ (gray curve in Figure 8).

(ii) the swallowtail curve is singular, so α is also a root of $a^2 + 2(b - a)\alpha - \alpha^2a$. Calculating the resultant of this polynomial and P we get $a^3(a^3 + (a - b)^2)^2 = 0$, which gives curves that are already present in the stratification.

Type 3 singularities stratum

These occur when $S_{(a_1, a_2)} = 0$ is tangent to $y = 0$. This occurs when

$$a_1 = \frac{1}{3b - 2a} a_2^2 + O_3.$$

Here we require $3b - 2a \neq 0$, so we have another stratum in the (a, b) -plane given by $3b - 2a = 0$. This is precisely the tangent line to the lips/beaks stratum at the origin.

Type 5 singularities stratum

These occur when the image of the singular set $h(0, y)$ is singular, and this happens when $a_1 = 0$ (for any value of the moduli).

The above strata exhaust all the possible codimension 1 local singularities that can occur in h . We turn now to the multi-local singularities.

Double point + fold stratum

Here a proper profile passes through the point of self-intersection (the double point) of the image of the singular set of the cuspidal edge. Thus we have $h(x_1, 0) = h(x_2, 0)$ for some $x_1 \neq x_2$, $S_{(a_1, a_2)}(x, y) = 0$ and $h(x_1, 0) = h(x, y)$.

From $h(x_1, 0) = h(x_2, 0)$ we get $x_2 = -x_1$ and $a_1 + bx_1^2 + dx_1^4 = 0$, so $a_1 = -bx_1^2 - dx_1^4$. We have now a system of five equations $S_{(-bx_1^2 - dx_1^4, a_2)}(x, y) = 0$ and $h(x_1, 0) = h(x, y)$ in x_1, x, y, a_2 . A necessary condition for the existence of a solution is $a^3 + (a - b)^2 > 0$ and $a \neq b$. Thus, there are no “double point + fold” singularities for (a, b) inside the cusp $\delta_P = a^3 + (a - b)^2 = 0$ where 3 swallowtail curves appear. When $a^3 - (a - b)^2 < 0$, calculations show that the “double point + fold” stratum is a regular curve parametrised by

$$a_1 = -\frac{b}{a^3 + (a - b)^2} a_2^2 + O_3.$$

Double point + Type 2 stratum

We have a double point on the image of the singular set of the cuspidal edge and a fold tangent to one of its branches at the double point. Thus $h(x_1, 0) = h(x_2, 0)$ for some $x_2 = -x_1$ (from above stratum) and $S_{(a_1, a_2)}(x_1, 0) = 0$ (or $S_{(a_1, a_2)}(-x_1, 0) = 0$). The stratum is again a regular curve parametrised by

$$a_1 = -\frac{b}{(a - b)^2} a_2^2 + O_3.$$

Type 2 + fold stratum

Here we have a Type 2 singularity together with another piece of the proper profile intersecting the two tangential curves transversally. Thus, we have a Type 2 singularity at $(x, 0)$ and there exists (x_1, y_1) , with $y_1 \neq 0$ such that $S_{(a_1, a_2)}(x, 0) = S_{(a_1, a_2)}(x_1, y_1) = 0$ and $h(x, 0) = h(x_1, y_1)$.

This stratum consists of 1 or 3 regular curves depending on whether the polynomial

$$Q(\lambda) = (a^3 + (a - b)^2)\lambda^3 - 3(a^3 + (a - b)^2)\lambda^2 + 3(a - b)^2\lambda + 4a^3 - (a - b)^2$$

has 1 or 3 roots. The discriminant of Q is $-108a^6(a - b)^2(a^3 + (a - b)^2)$. In particular, we have 1 (resp. 3) regular curves if and only if the swallowtail stratum consists of 1 (resp. 3) regular curve(s).

The initial part of the parametrisation of the curve(s) is

$$a_1 = \frac{4(\lambda - 1)((3b - 3a)\lambda^2 - (3a\mu + 3b - 2a)\lambda + a)}{((3b - 3a)\lambda^2 - 3a\mu\lambda - 3b + 3a)^2} a_2^2 + O_3,$$

with $\mu = -\sqrt{a(1 - \lambda^2)}$ and λ a root of the polynomial Q .

Triple point stratum

We have three pieces of the proper apparent contour intersecting transversally at a given point, so we need to solve $h(x_1, y_1) = h(x_2, y_2) = h(x_3, y_3)$ in (a_1, a_2) , with $(x_i, y_i) \neq (x_j, y_j)$ for $i \neq j$. The stratum is empty in the examples in Figures 9, 10, 11, 12 and consists of a regular curve in the case of Figure 13. For the general case, the equations are too lengthy to reproduce here and eliminating variables leads to equations of very high order.

Tacnode stratum

This consists of a multi-local singularity where the proper apparent contour has an ordinary tangency with the image of the cuspidal curve. The stratum consists of one regular curve if $b > -\frac{4}{27}$ and 3 regular curves if $b < -\frac{4}{27}$ (and $ab \neq 0$) parametrised by

$$a_1 = \frac{(-a\lambda^4 + 2b\lambda^3 + (a\mu + 2a - 3b)\lambda^2 - a\mu - a + b)(\lambda - 1)^2}{((b - a)\lambda^3 - a\mu\lambda^2 + (3a\mu + 3a - 3b)\lambda - 2a\mu + 2b - 2a)^2} a_2^2 + O_3,$$

with λ a solution of

$$(a^3 - (a + b)^2)\lambda^3 + (3a^3 + 4b^2 - (a - b)^2)\lambda^2 + (3a^3 - 3b^2 + (a + b)^2)\lambda + a^3 + (a - b)^2 = 0$$

and $\mu = -\sqrt{-a(1 - \lambda^2)}$.

Cusp + fold

We have a cusp on the proper apparent contour on the image of the singular set of the cuspidal edge. Here we get two regular curves given by

$$a_1 = \frac{4}{9} \frac{(3a^2 + (3b - 4a)\beta - \beta^3)\beta}{(a^2 + 2(b - a)\beta - a\beta^2)^2} a_2^2 + O_3,$$

with β one of the two real roots of

$$3a^5 - 4a^3(a - b)\beta + 6\beta^2a^4 - 12a^2(a - b)\beta^3 + (4(a - b)^2 - a^3)\beta^4.$$

We draw in Figures 9, 10, 11 three possibilities for the bifurcations of the proper apparent contour and of the projections of the singular set for the lips Type 7 singularity. Figures 12,

13 are for the bifurcations of a beaks Type 7 singularity with one figure having one swallowtail stratum and the other 3 swallowtail strata. As Figure 8 shows, there are various open strata in the (a, b) -plane and in each stratum we have distinct bifurcations of the apparent contour. We observe that the stratification in Figure 8 is a partial one as we have not included, for instance, where the various curves in the stratification of the (a_1, a_2) -plane are inflectional nor where their relative position changes. Figures 9-13 and Figure 8 show the richness of the extrinsic differential geometry of the cuspidal edge. \square

REMARK 4.6. In the calculations in the proof of Theorem 4.5 for the Type 7 singularity, we eliminate variables using resultant (using Maple) until we get an equation $g = 0$ involving only two variables. The function germ g is finitely \mathcal{R} -determined and has a well understood singularity (in the cases involved), so we can deduce the smooth structure of $g = 0$ and, in particular, the number of its branches and the initial parametrisation of each branch. We reverse the process until we get the initial part of the local parametrisation of the desired stratum.

Finally, we consider geometric criteria for recognition of the generic singularities of the orthogonal projections of the cuspidal edge M . We denote by $TC_p M$ the tangent cone to M at a point p on the singular set Σ and by \mathbf{v}_{tg} the tangential direction at p .

Proposition 4.7. *For a generic cuspidal edge, the projection $P_{\mathbf{v}}$ can have one of the local singularities in Table 2 and these occur at a point $p \in \Sigma$ when the following geometric conditions are satisfied.*

- (i) *If \mathbf{v} is transverse to the tangent cone $TC_p M$, then $P_{\mathbf{v}}$ has a singularity of Type 1.*
- (ii) *If $\kappa_n(p) \neq 0$, for all directions in $TC_p M \setminus \{\mathbf{v}_{tg}\}$ except for one \mathbf{v}_0 , the singularity of $P_{\mathbf{v}}$ is of Type 2. The singularity of $P_{\mathbf{v}_0}$ is of Type 3 at generic points on Σ and becomes of Type 4 at isolated points on Σ . The two types Type 3 and Type 4 are distinguished by the contact of the proper contour generator with Σ , two for Type 3 and three for Type 4. If $\kappa_n(p) = 0$ but $\kappa_t(p) \neq 0$, the singularity of $P_{\mathbf{v}}$ is of Type 2 for all $\mathbf{v} \in TC_p M \setminus \{\mathbf{v}_{tg}\}$. If $\kappa_n(p) = \kappa_t(p) = 0$, the singularity of $P_{\mathbf{v}}$ is of Type 3 for all $\mathbf{v} \in TC_p M \setminus \{\mathbf{v}_{tg}\}$ except for one direction where it becomes of Type 4.*
- (iii) *The singularity of $P_{\mathbf{v}_{tg}}$ is of Type 5 if $\tau_{\Sigma}(p)\kappa_n(p) \neq 0$, generically of Type 6 if $\tau_{\Sigma}(p) = 0$ and $\kappa_n(p) \neq 0$, and generically of Type 7 if $\kappa_n(p) = 0$.*

Proof. Following the transversality theorem in the Appendix of [8], for a generic cuspidal edge only singularities of ${}_X\mathcal{A}_e$ -codimension ≤ 2 (of the stratum) occur in the projection $P_{\mathbf{v}}$ (i.e., those listed in Table 2).

The kernel direction of $(dP_{\mathbf{v}})_p$ is parallel to the direction of projection \mathbf{v} . The relative position of the kernel direction with respect to the tangent cone and the tangential direction is invariant under diffeomorphism, so can be considered on a submersion g on the model X . It follows from the classification in the proof of Theorem 4.3, that g has a singularity of Type 1 at p when the kernel direction of dg_p is transverse to the tangent cone $TC_p X$, a singularity of Type 2,3,4 if the kernel direction is in $TC_p X$ but is not the tangential direction at p , and of Type 5,6,7 if the kernel direction is parallel to the tangential direction.

We take the cuspidal edge parametrised as in (1). Suppose that $\mathbf{v} = (\alpha, \beta, 0) \in TC_p M$ with $\alpha^2 + \beta^2 = 1$ and take p to be the origin. Consider the projection $\Pi_{\mathbf{v}}(u, v, w) = ((1 -$

$\alpha^2)u - \alpha\beta v, -\alpha\beta u + (1 - \beta^2)v, w)$. By rotating the plane of projection $T_{\mathbf{v}}S^2$ to the plane $u = 0$ and rescaling we get $\Pi_{\mathbf{v}}(u, v, w) \sim_{x\mathcal{A}} (\beta u - \alpha v, w)$. We shall modify the family of projections and take $\Pi_{\mathbf{v}}(u, v, w) = (\beta u - \alpha v, w)$.

Suppose that $\mathbf{v} \neq \mathbf{v}_{tg}$ (i.e., $\beta \neq 0$; we can then set $\beta = 1$). Following the proof of Theorem 4.5, the singularities of Type 2, 3 and 4 are distinguished by the contact of the proper contour generator with the singular set Σ . We have

$$P_{\mathbf{v}}(x, y) = (\alpha x - (a(x) + \frac{1}{2}y^2), b_1(x) + y^2b_2(x) + y^3b_3(x, y)).$$

The singular set of $P_{\mathbf{v}}$ is given by $yS_{\alpha}(x, y) = 0$ with

$$\begin{aligned} S_{\alpha}(x, y) = & (\alpha b_{20} + b_{12})x + \frac{1}{2}b_{03}y + \\ & + (\frac{1}{2}\alpha b_{30} + b_{22} - \alpha a_{20}b_{12})x^2 + \frac{1}{2}(b_{13} - \alpha a_{20}b_{03})xy + \frac{1}{2}\alpha b_{12}y^2 + \\ & + \alpha(\frac{2}{3}b_{40} - \frac{1}{2}a_{30}b_{12} - a_{20}b_{22})x^3 - \frac{\alpha}{4}(a_{30}b_{03} + 2a_{20}b_{13})x^2y + \alpha b_{22}xy^2 + \\ & + \frac{1}{6}\alpha b_{13}y^3 + O(4). \end{aligned}$$

The singular set $S_{\alpha} = 0$ is transverse to Σ unless $\alpha b_{20} + b_{12} = 0$. If $b_{20} = \kappa_n(p) \neq 0$, then there is a unique direction \mathbf{v}_0 parallel to $(-b_{12}, b_{20}, 0)$ where transversality fails (so $\alpha = \alpha_0 = -b_{12}/b_{20}$). The singular set $S_{\alpha_0} = 0$ has contact of order 2 with Σ at the origin if $2b_{12}^2a_{20} - b_{12}b_{30} + 2b_{22}b_{20} \neq 0$. The contact is of order 3 if $2b_{12}^2a_{20} - b_{12}b_{30} + 2b_{22}b_{20} = 0$ and $\alpha_0(\frac{2}{3}b_{40} - \frac{1}{2}a_{30}b_{12} - a_{20}b_{22}) \neq 0$.

Suppose now that $b_{20} = \kappa_n(p) = 0$. Then transversality of S_{α} with Σ fails if and only if $b_{12} = \kappa_t(p) = 0$. In this case the singularity of $P_{\mathbf{v}}$ is of Type 3 unless $\alpha = \alpha_0 = -2b_{22}/b_{30}$, where it becomes of Type 4.

When $\mathbf{v} \neq \mathbf{v}_{tg} = (1, 0, 0)$, we have $P_{\mathbf{v}_{tg}}(x, y) = (a(x) + \frac{1}{2}y^2, b_1(x) + y^2b_2(x) + y^3b_3(x, y))$ and its critical set is given by $yS_{\mathbf{v}_{tg}}(x, y) = 0$ with

$$S_{\mathbf{v}_{tg}}(x, y) = -b_{20}x + (b_{12}a_{20} - \frac{1}{2}b_{30})x^2 + \frac{1}{2}a_{20}b_{03}xy - \frac{1}{2}b_{12}y^2 + O(3).$$

From the proof of Theorem 4.5, the singularity of $P_{\mathbf{v}_{tg}}$ is of Type 5 (resp. Type 6) if $S_{\mathbf{v}_{tg}} = 0$ is a regular curve and the image of Σ by $P_{\mathbf{v}_{tg}}$ is an ordinary (resp. ramphoid) cusp. Now $\Sigma_{\mathbf{v}_{tg}}$ is a regular curve if and only if $b_{20} = \kappa_n(p) \neq 0$. The image of Σ is $P_{\mathbf{v}_{tg}}(x, 0) = (a(x), b_1(x))$. It has an ordinary cusp if and only if $b_{30}a_{20} - a_{30}b_{20} \neq 0$, that is $\tau_{\Sigma}(p) \neq 0$. When $\tau_{\Sigma}(p) = 0$, the singularity is generically a ramphoid cusp. When $b_{20} = 0$, $S_{\mathbf{v}_{tg}}$ is singular so we have generically a singularity of Type 7. \square

ACKNOWLEDGEMENTS. We would like to thank Juan José Nuño Ballesteros for useful discussions. We would also like to thank the referee for the careful reading of the paper and suggestions.

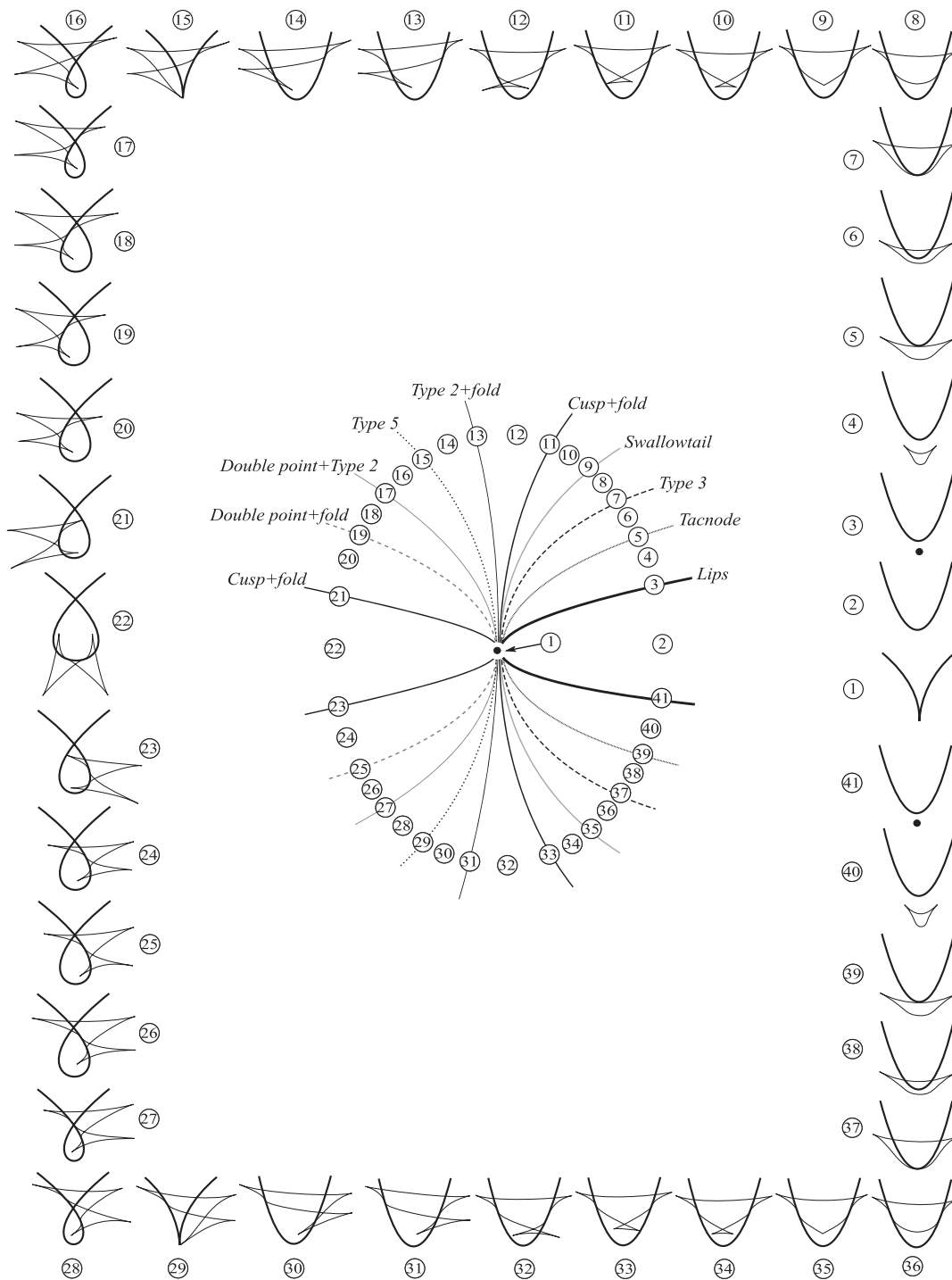


Fig. 9. Lips type bifurcations in the proper apparent contour and of the projections of the singular set at a Type 7 singularity with (a, b) in Region ① in Figure 8.

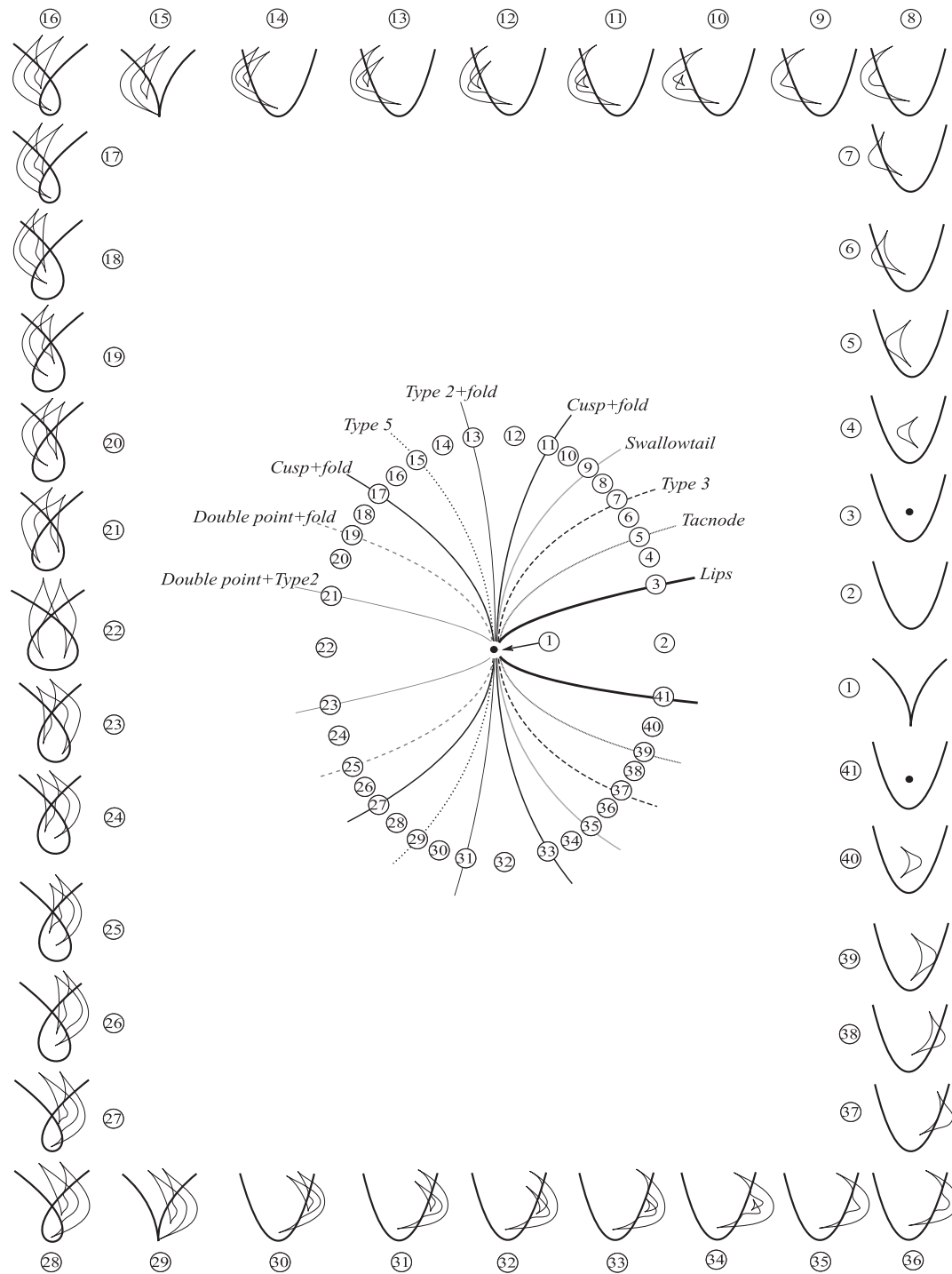


Fig. 10. Lips type bifurcations in the proper contour and of the projections of the singular set at a Type 7 singularity with (a, b) in Region ② in Figure 8.

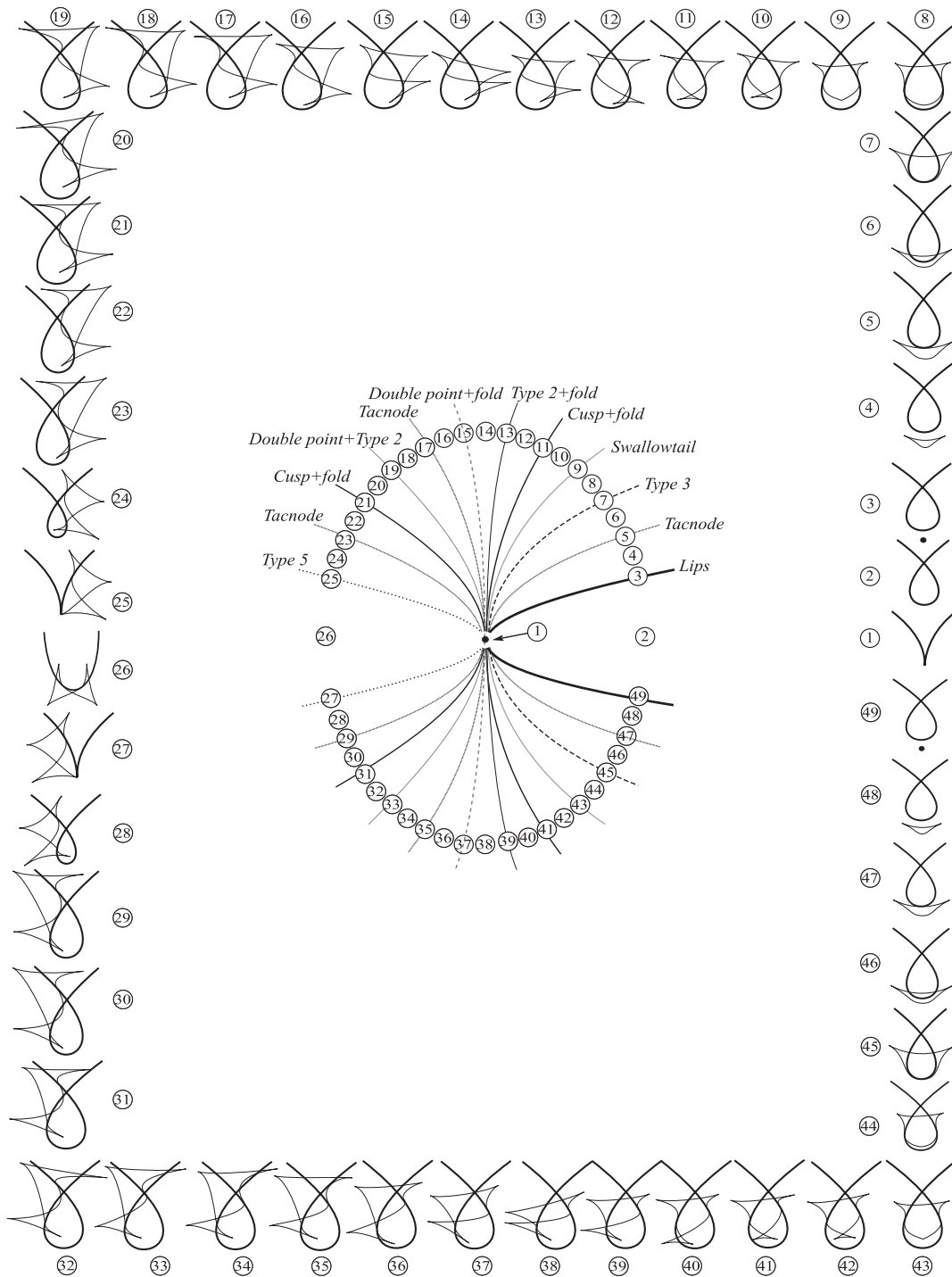


Fig. 11. Lips type bifurcations of the proper contour and of the projections of the singular set at a Type 7 singularity with (a, b) in Region ③ in Figure 8.

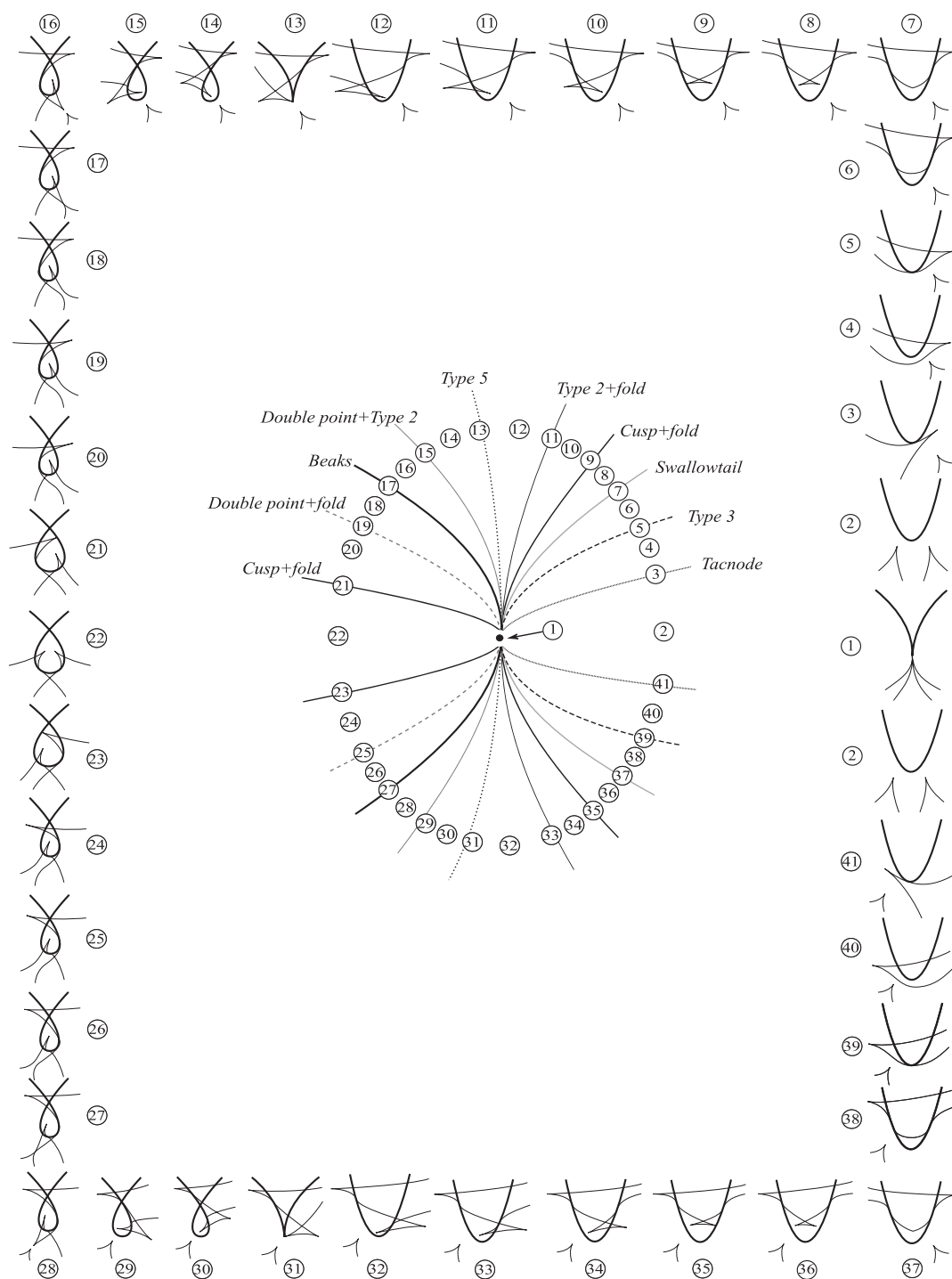


Fig. 12. Beaks type bifurcations of the proper contour and of the projections of the singular set at a Type 7 singularity with (a, b) in Region ④ in Figure 8.

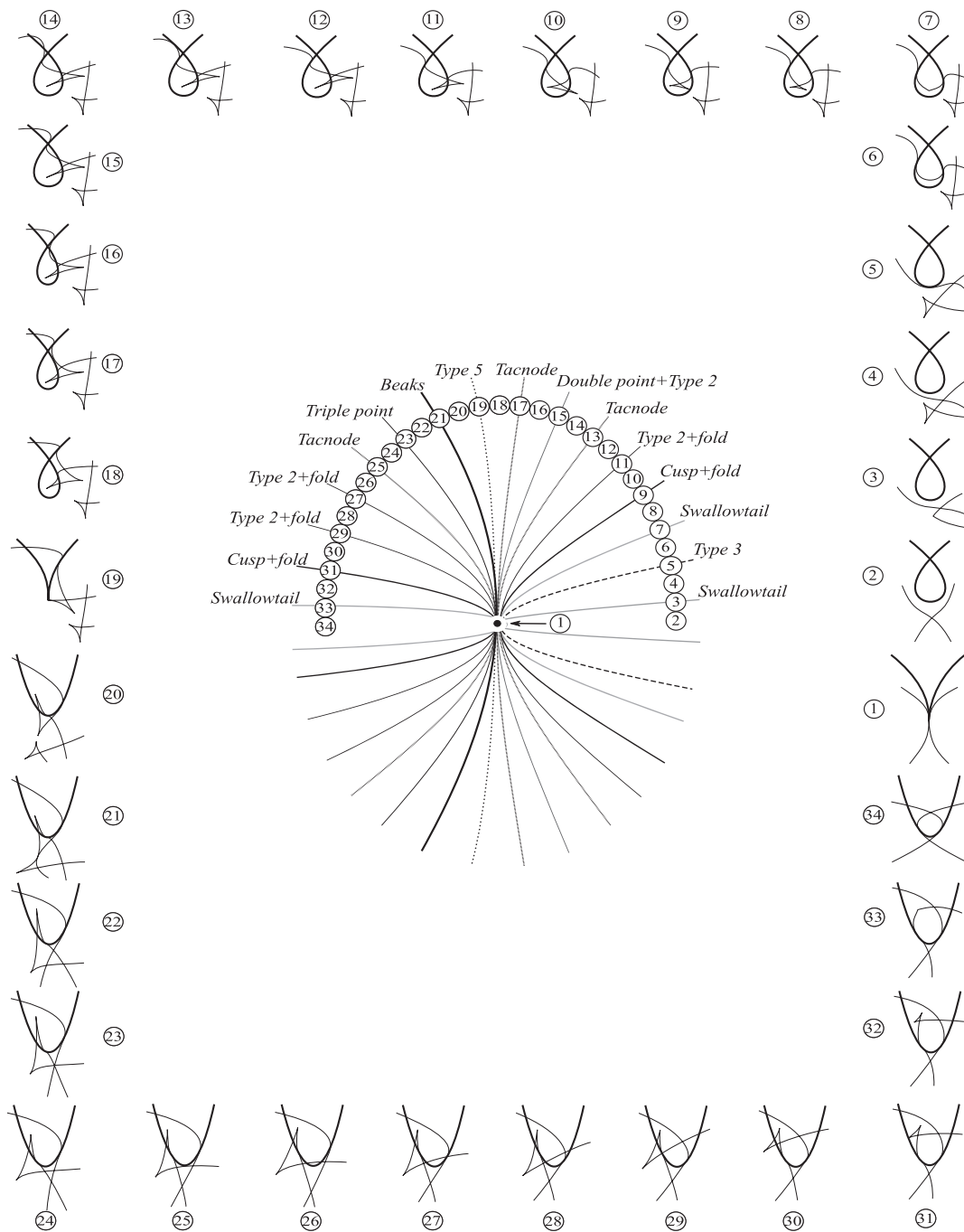


Fig. 13. Beaks type bifurcations of the proper contour and of the projections of the singular set at a Type 7 singularity with (a, b) in Region ⑤ in Figure 8. The figure for (a_1, a_2) with $a_2 < 0$ is the reflection with respect to the y -axis of the figure for $(a_1, -a_2)$ and is omitted for lack of space.

References

- [1] M. Barajas Sichaca and Y. Kabata: *Projections of the cross-cap*, preprint, 2015.
- [2] J.W. Bruce and P.J. Giblin: *Curves and singularities*, Cambridge University Press, Cambridge, 1992.
- [3] J.W. Bruce and P.J. Giblin: *Projections of surfaces with boundary*, Proc. London Math. Soc. **60** (1990), 392–416.
- [4] J.W. Bruce, P.J. Giblin and F. Tari: *Families of surfaces: height functions, Gauss maps and duals*; in Real and complex singularities (São Carlos, 1994), Pitman Res. Notes Math. Ser. **333** (1995), 148–178.
- [5] J.W. Bruce, N.P. Kirk and A.A. du Plessis: *Complete transversals and the classification of singularities*, Nonlinearity **10** (1997), 253–275.
- [6] J.W. Bruce, A.A. du Plessis and C.T.C. Wall: *Determinacy and unipotency*, Invent. Math. **88** (1987), 521–554.
- [7] J.W. Bruce and R.M. Roberts: *Critical points of functions on analytic varieties*, Topology **27** (1988), 57–90.
- [8] J.W. Bruce and J.M. West: *Functions on a crosscap*, Math. Proc. Cambridge Philos. Soc. **123** (1998), 19–39.
- [9] J.W. Bruce and T.C. Wilkinson: *Folding maps and focal sets*; in Singularity theory and its applications, Part I, Lecture Notes in Math. **1462**, Springer, Berlin, 1991, 63–72.
- [10] J.N. Damon, P.J. Giblin and G. Haslinger: *Local Features in Natural Images via Singularity Theory*, Lecture Notes in Mathematics **2165**, Springer, 2016.
- [11] J.N. Damon: *Topological triviality and versality for subgroups of \mathcal{A} and \mathcal{K}* , Mem. Amer. Math. Soc. **75** (1988), no. **389**.
- [12] T. Gaffney: *The structure of the $TA(f)$, classification and application to differential geometry*; in Singularities, Part I (Arcata, Calif., 1981), Proc. Sympos. Pure Math. **40** (1983), 409–427. Amer. Math. Soc., Providence, RI.
- [13] C.G. Gibson and C.A. Hobbs: *Singularities of general one-dimensional motions of the plane and space*, Proc. Roy. Soc. Edinburgh Sect. A **125** (1995), 639–656.
- [14] S. Izumiya, M.C. Romero Fuster, M.A.S. Ruas and F. Tari: *Differential geometry from singularity theory viewpoint*, World Scientific Publishing Co. Pte. Ltd., Hackensack, NJ, 2016.
- [15] N.P. Kirk: *Computational aspects of classifying singularities*, LMS J. Comput. Math. **3** (2000), 207–228.
- [16] J.J. Koenderink: *Solid Shape*, MIT Press, Cambridge, MA, 1990.
- [17] L. Martins and J.J. Nuño Ballesteros: *Contact properties of surfaces in \mathbb{R}^3 with corank 1 singularities*, Tohoku Math. J. **67** (2015), 105–124.
- [18] L. Martins and K. Saji: *Geometric invariants of cuspidal edges*, Canad. J. Math. **68** (2016), 445–462.
- [19] K. Naokawa, M. Umehara and K. Yamada: *Isometric deformations of cuspidal edges*, Tohoku Math. J. **68** (2016), 73–90.
- [20] J.H. Rieger: *Families of maps from the plane to the plane*, J. London Math. Soc. **36** (1987), 351–369.
- [21] J.H. Rieger and M.A.S. Ruas: *Classification of \mathcal{A} -simple germs from \mathbb{K}^n to \mathbb{K}^2* , Compositio Math. **79** (1991), 99–108.
- [22] K. Saji, M. Umehara and K. Yamada: *The geometry of fronts*, Ann. of Math. (2) **169** (2009), 491–529.
- [23] F. Tari: *Projections of piecewise-smooth surfaces*, J. London Math. Soc. **44** (1991), 155–172.
- [24] K. Teramoto: *Parallel and dual surfaces of cuspidal edges*, Differential Geom. Appl. **44** (2016), 52–62.
- [25] C.T.C. Wall: *Geometric properties of generic differentiable manifolds*; in Geometry and topology: proceedings of the school held at the Instituto de Matemática Pura e Aplicada CNPq, Rio de Janeiro, July 1976, Lecture Notes in Math. **597** Springer, Berlin, 1977, 707–774.
- [26] J.M. West: *The differential geometry of the crosscap*, Ph.D. thesis, The University of Liverpool, 1995.
- [27] T.C. Wilkinson: *The geometry of folding maps*, Ph.D. thesis, University of Newcastle-upon-Tyne, 1991.

Raúl Oset Sinha
Departament de Geometria i Topologia
Universitat de València
c/ Dr Moliner no 50, 46100, Burjassot, València
Spain
e-mail: raul.oset@uv.es

Farid Tari
Instituto de Ciências Matemáticas e de
Computação - USP, Avenida Trabalhador são-carlense
400 - Centro
CEP: 13566-590 - São Carlos - SP
Brazil
e-mail: faridtari@icmc.usp.br